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**Studies on ecological evaluation of
reach-scale channel configuration based on
habitat structure and biodiversity relations**

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A Dissertation

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for the Degree of Doctor of Engineering
of
Kyoto University, Japan**

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Abstract

Many rivers in developed countries had experienced deterioration of habitat conditions under various human impacts such as a channelization and/or dam construction. In order to restore the healthy habitats in these rivers, it is required to develop river management methods aiming at reformation and maintenance of ecologically appropriate riverbed geomorphology. However, previous studies on causal relationships among hydro-geomorphic conditions, habitat structure and biodiversity are not yet enough for planning such restoration works in the scene.

Since reach-scale channel configuration (RSCC) such as braided, meandering, or straight channels will determine habitat characteristics, hydro-geomorphic prediction of RSCC could be a powerful device for prediction of ecological changes in rivers under human impacts on basin environments.

This study aims at investigating on interrelationships among RSCC, habitat structure and biodiversity in the Kizu River, a typical semi natural sediment rich river in Japan. Although the Kizu River changed from braided channels to wandering channels having alternative bars with significant vegetation expansion after sand excavation and dam construction, bared-bars were still readily visible, and lentic habitats providing habitat to bitterling and mussel had been developed. Investigation in the Kizu River could contribute for understanding natural and semi-natural interrelationships.

There are three main purposes in this study: i.e., 1) to present empirical relations between RSCC and habitat structure using historical data on the riverbed geomorphology, 2) to demonstrate relations among RSCC, aquatic habitat structures and species richness and/or abundance of fish and mussels, and 3) to propose countermeasures for integrated riverbed management based on ecological evaluation of RSCC. Following six studies were performed for the purposes.

In chapter 1, improvement point of previous studies and scheme of this study were described.

In chapter 2, Relations between aquatic habitat structure and RSCC, and those

between RSCC and disturbance regimes were investigated using 9 sets of aerial photos and cross-sectional measurements taken in recent 65 years from 1948 to 2012 in the lower reaches of the Kizu River. A total of 8 RSCC types were classified based on reach-scale geomorphological parameters: single; slightly wandering straight and sinuous; quite wandering straight and sinuous; bifurcated wandering straight and sinuous and braided channels. Aquatic habitats were classified into 4 lotic habitats (main-slow, secondary-slow, gently bending riffle, sharply bending riffle) and 4 lentic habitats (bar-head wando, bar-tail wando, active pond, terrace pond), and their diversity indices (richness, evenness, diversity, soundness) were analyzed in relation to RSCC variation. The results showed bifurcated wandering channels are more stabilized than braided channels tended to have diverse and abundant lentic and lotic habitats, although braided channels tended to have abundant lotic habitats. Analyses on relations between RSCC and disturbance showed a result of positive relations of intensity of discharge and volume of sediment transport to the number of bifurcated wandering and braided channels.

In chapter 3, relations among abundance of bitterling and mussel communities, habitat structures and RSCC was described. A total of 120 ponds on the lateral bars and terraces were monitored on fish and mussel communities with habitat conditions in 2007 and 2010. These ponds were classified into bar head-active pond (BH-AP), bar head-terrace pond (BH-TP), bar tail-active pond (BT-AP) and bar tail-terrace pond (BT-TP). Flooding frequency was used as a key parameter reflecting habitat conditions for bitterlings and mussels, and floodplain vertical shape index (FVSI) was used as characteristic of RSCC. Results showed that terrace ponds had more abundance of bitterlings and mussels than active ponds, and the terrace ponds with flood frequency of 8- 22 days per year had the most bitterlings and mussels. Number of these terrace ponds tended to increase on slightly wandering channels with slightly concave floodplain shape. Analyses on historical changes in riverbed geomorphology showed that RSCC after the 1980s of the Kizu River have had a higher potential of habitat suitability for bitterlings and mussels than before

In chapter 4, historical influence of the past environmental conditions on present richness of species in lentic habitats was shown. Richness of fish, bitterlings and

mussels in lentic habitats (active pond and terrace ponds) were analyzed to not only present environmental habitat conditions but also the past conditions in lentic habitat structures using principal component analysis (PCA) and generalized linear model (GLM). The results indicated richness of bitterlings could be best described by a model consisting of conditions one year ago, and mussels were explained by a model two years ago, whereas richness of resident and alien fish were correlated with habitat conditions of a current year.

In chapter 5, countermeasures were proposed for riverbed management based on methods of evaluation of RSCC in relation to habitat diversity and bitterling/mussel. As short term countermeasure, increasing channel width about 1.8 - 2.0 times could positively influence on biodiversity based on relations between RSCC in the Kizu River and hydro-geomorphic parameters (width/depth ratio and specific stream power). In addition, at around 40,000 - 50,000 m³/yr in the volume of sediment transport is required for biodiversity as long term countermeasure.

In chapter 6, method of ecological evaluation of RSCC and its application to riverbed management in the Kizu River were concluded.

Contents

Chapter 1. Introduction	1
1.1 For better river management.....	1
1.1.1 Previous studies.....	2
1.1.2 New concept of river management with geomorphic habitat approaches	3
1.1.3 Reach-scale channel configuration (RSCC)	4
1.2 Subject of this study.....	11
1.3 Introduction of the Kizu River.....	13
1.4 Chapter outline.....	16
 Chapter 2. Relations of reach scale channel configuration (RSCC) to habitat structure.....	19
2.1 Introduction.....	20
2.2 Methods	23
2.2.1 Study area	23
2.2.2 Materials	23
2.2.2 Parameters of RSCC.....	25
2.3.3 Classification of habitat structures.....	29
2.3.4 Statistical analyses.....	30
2.3 Results.....	33
2.3.1 Historical changes in habitat structures and RSCC.....	33
2.3.2 Relations of habitat structures and RSCC	35
2.3.3 Relations of RSCC and disturbance	39
2.4 Discussion	42
2.4.1 Which types of channel types are suitable for habitat diversity?	42
2.4.2 Effects of reduction of disturbance on RSCC and habitat structure	44
2.4.3 Application of channel type classification to riverbed management	45
2.5 Conclusion	46

Chapter 3. Evaluation of RSCC based on bitterling-mussel abundance and lentic

habitat structure	49
3.1 Introduction.....	50
3.2 Methods	52
3.2.1 Study area	52
3.2.2 Abundance of species.....	52
3.2.3 Parameters of habitat conditions and habitat types.....	53
3.2.4 Reach scale channel configuration	53
3.2.5 Statistical analyses.....	54
3.3 Results.....	54
3.3.1 Abundance of bitterlings and mussels in habitat conditions and types .	54
3.3.2 Relations of habitat conditions to bitterlings and mussels	55
3.3.3 Relations of representative habitat conditions to RSCC	59
3.3.4 Historical changes of FVSI	61
3.4 Discussion	61
3.4.1 Suitable habitat conditions for the abundance of bitterlings and mussels	61
3.4.2 Volume of sediment required for suitable habitats for bitterlings and mussels	63
3.5 Conclusion	65

Chapter 4. Historical influence of past environmental conditions on the present

biodiversity in lentic habitat	67
4.1 Introduction.....	68
4.2 Method	69
4.2.1 Study sites.....	69
4.2.2 Species richness.....	70
4.2.3 Parameters of habitat conditions	70
4.2.4 Statistical analyses.....	71
4.3 Results.....	72
4.3.1 Annual changes of habitat conditions	72
4.3.2 Relations between species richness and habitat conditions.....	73
4.4 Discussion	76
4.5 Conclusion	78

Chapter 5. Ecological evaluation of RSCC and its application to riverbed management	81
5.1 Introduction.....	81
5.2 Methods	86
5.2.2 Hydro-geomorphic parameters	86
5.3 Results.....	87
5.3.1 Relations of RSCC to hydro-geomorphic parameters	87
5.3.2 Changing channels by increase/decrease of channel width	90
5.3.3 Summary of suitable sediment volume of biodiversity.....	92
5.4 Discussion.....	93
5.4.1 Proposal of short- term countermeasure for biodiversity	93
5.4.2 Proposal of long-term countermeasures for biodiversity	94
5.4.3 Framework of ecological riverbed management in the Kizu River	95
 Chapter 6. Conclusion	 101
 References.....	 104
 Acknowledgements.....	 112

List of figures

Fig 1.2 Framework in habitatology by Takemon (2007).....	4
Fig. 1.3 Image of classification of RSCC by Schumm (1985).....	6
Fig. 1.4 Channel patterns (a) by slope and discharge (Leopold and Wolman, 1957) (b) by slope/Froude number and width/depth ratio (Parker , 1976) (c) by sinuosity and slope (Schumm and Khan (1972)	8
Fig. 1.4 Channel patterns (d) by stream power in bankfull discharge and grain size (Van den Berg, 1995). P=sinuosity (e) by depth/grain size ratio and width/depth ratio (Muramoto and Fujita,1977) (f) by Width/depth ratio and specific stream power (Van den Berg,1995; Burge, 2005).....	9
Fig. 1.5 Classification of RSCC by Brierley and Fryirs (2005) from Brierley et al. (2002)	10
Fig. 1.6 A map of the Kizu River basin	13
Fig. 1.7 Evaluated volume of sediment transport by Takemon etl al., (2013).....	14
Fig. 1.8 Historical changes in (a) 1948 (b) 1961 (c) 1971 (d) 1990 (e) 2010 between 7-10 km	15
Fig. 1.9 Chapter outline.....	18
Fig. 2.1 Historical changes of discharge; (a) annual peak discharge from 1956 to 2011, and (b) hourly discharge from 1970 to 2012 at Inooka station (16 km from conjunction) in the Kizu River.	24
Fig. 2.2 Image of Floodplain Vertical Shape Index (FVSI).....	27
Fig. 2.3 Image of channel patterns	28
Fig. 2.4 Geomorphological characteristics of channel types; (a) channel width, (b) Floodplain vertical shape index (FVSI), (c) bed slope, and (d) ratio of vegetation area (wood +bush-land).....	34
Fig. 2.5 Historical changes in the number of reaches showing each channel type in the Kizu River	35
Fig. 2.6 Comparison of abundance of 9 habitat types among 8 channel types in the Kizu River based on all the data in 1948-2012	36
Fig. 2.7 Relations of abundance of each habitat (n/2km) to channel types (mean values and SD).	37

Fig.2.8 Relations of (a) habitat richness, (b) habitat evenness, (c) habitat diversity and (d) habitat soundness to channel types (mean values and SD).....	38
Fig. 2.9 Relation of abundance of channel types to disturbance regime; (a) annual sediment transport, (b) Qmax (maximum discharge), (c) Fn3000 (Number of flood events exceeding Q3000) per year.....	40
Fig. 3.1 Mussel life (a), egg of bitterling in mussel (b), bitterling (c)	51
Fig. 3.2 Relations of (a) mud depth to abundance of bitterlings and (b) wood coverage to abundance of mussels	57
Fig. 3.3 Relations of flooding frequency to (a) relative height, (b) mud depth and (c) wood coverage.....	57
Fig. 3.4 Relations of flooding frequency to (a) SI of bitterlings and (b) SI of mussels.....	58
Fig. 3.5 Relations of floodplain vertical shape index (FVSI) to (a) ratio of number of ponds with different flood frequencies and (b) number of pond types	60
Fig. 3.6 Historical changes of FVSI; rectangles indicate mean values each year	61
Fig. 3.7 Sediment transport required for bitterling and mussel	64
Fig. 4.1 Analyzed data of 4 years with annual discharge.	71
Fig. 4.2 Annual changes of habitat conditions (a) depth of mud, (b) DO, (c) ratio of vegetation coverage, (d) covered ratio by floating plants on water surface	72
Fig. 4.3 Relations between (a) habitat age and species richness of bitterlings, (b) depth of mud and species richness of mussels and (c) vegetation coverage and species richness of alien fish.....	76
Fig. 4.4 Life cycle of mussels (source: Texas Parks and Wildlife).....	78
Fig. 5.1 Classification of RSCC in the Kizu River.....	84
Fig. 5.2 Evaluated RSCC by habitat diversity and soundness.....	85
Fig. 5.3 (a) Evaluated RSCC using FVSI by habitat diversity and (b) relations between FVSI and channel types.	85
Fig. 5.4 Ranges of RSCC in the biplot dimension of bankfull discharge and channel slope (Latrubesse, 2008)	87
Fig. 5.5 Channel types in the Kizu River in the biplot dimension of depth/grain size ratio and width/depth ratio.....	88
Fig. 5.6 (a) Distribution of each channel type within the biplot dimension of width/depth ratio	

and specific stream power in the Kizu River and (b) their historical changes in channel types, the plots of 0-2km, 10-12 km and 18-20 km correspond to those in lower, middle and upper reaches of the study area.....	89
Fig. 5.7 Prediction method for resultant RSCC after manipulation of channel width. The countermeasure can be evaluated by the resultant RSCC plots in relation to the potential ranges for ecological functions.....	91
Fig.5.8 Volume of sediment transport required for biodiversity.....	92
Fig. 5.9 Ecological riverbed management in the Kizu River.....	96
Fig. a-1 Calculation of reach-scale geomorphological parameters.....	97
Fig. a-2 Methods of calculation of FVsI (Takemon et al., 2013).....	99
Fig. a-3 (a) Classification of habitat structure using aerial photo (b) bar-head wando (c) bar-tail wando (d) riffle (e) active pond (f) terrace pond	100

List of tables

Table 1.1 Description of classification of RSCC in plan view	5
Table 2.1 Historical changes of flow regime and annual sediment transport of the Kizu River between 1961 and 2012	25
Table 2.2 Parameters of RSCC measured using aerial photographs and cross-section data in the Kizu River. All the parameters were measured per 2 km unit.	26
Table 2.3 Classification of channel types in the Kizu River.....	28
Table 2.4 Classification of aquatic habitats based on aerial photographs in the Kizu River	30
Table 2.5 Historical changes in habitat structures and reach-scale geomorphological parameters (mean \pm standard error) in the Kizu River between 1948 and 2012.....	31
Table 3.1 Discharge per flooding frequency at Innooka observatory (16km from conjunction)	53
Table 3.2 Habitat conditions per habitat types.....	55
Table 3.3 Abundance of bitterlings and mussels across all 120 ponds and each pond type (mean \pm standard error).	55
Table 3.4 Results of multiple regression analysis that examined the best models of habitat conditions for abundance of bitterlings and mussels	56
Table 4.1 Results of generalized linear model tested the relations of species richness in 2011 and habitat conditions in 2007, 2009, 2010 and 2011. n is number of used parameters ...	74
Table 4.2 Results of correlation analysis tested relations between species richness and habitat conditions were used in model.	75

Chapter 1. Introduction

1.1 FOR BETTER RIVER MANAGEMENT

As natural hazards often bring severe disasters to human society, most of governments have constructed artificial structures, such as check dams and reservoir dam, to prevent sediment and flood disasters. However, as a result of these facilities, most rivers in developed centuries have lost sediment dynamism and geomorphic activity and thereby biodiversity. In other words, reduction of sediment load and confined discharges cause downstream reaches to be starved of sediment and facilitate channel erosion and bank failure (Kondolf, 1997) and thus influence habitat loss (Schumm, 1985) and reduction of biodiversity (Hupp et al., 2009). Because a lot of organisms on the earth have adapted to conditions of disturbed habitats (Takemon, 1997), reduction in the frequency and/or intensity of floods has a negative impact on fauna or flora, such as increasing exotic species and causing protected species to disappear. In order to restore the healthy habitats in these rivers, it is necessary to develop river management methods for assessing the ecological conditions of rivers and for linkage between ecological and hydraulic conditions in a hierarchical manner.

1.1.1 Previous studies

Most previous studies used hydraulic parameters as explanatory factors for the assessment of ecological conditions (Fig 1.1). Ecohydraulic models, such as IFIM and PHABSIM (Physical Habitat Simulation Model), were effective in assessing physical habitat conditions (Pasternack et al., 2008). However, although this model could predict suitable habitat conditions, it used hydraulic habitat conditions such as depth, velocity and substrate as independent factors of each other. Similarly, the model of HEP (Habitat Evaluation Procedure, US Fish and Wildlife Service) is used to measure independent factors for evaluation of habitat conditions, although the model could select various habitat conditions, and give weighted value. These models can assess ecological conditions and predict alterations of habitat conditions using hydrogeomorphic configuration. However, values of each parameter are easily changed by the surveyed point or timing, and it is difficult to detect suitable sites where one is satisfied with various conditions at the same time. Thus, it is difficult to use these independent parameters as targets when we determine target conditions for river management. Otherwise, many studies about relations between biodiversity and environmental/geomorphic conditions used principal component analysis (PCA) to understand their correlations (Terada et al., 2011). Although converted parameters reflecting various conditions in this method could describe the degree of influence, these virtual parameters without substance also could not be used as target conditions or explanatory factors for river management. For applying to biodiversity in river management, species abundance or diversity should be related with hydraulic parameters such as discharge or flow through a visible target.

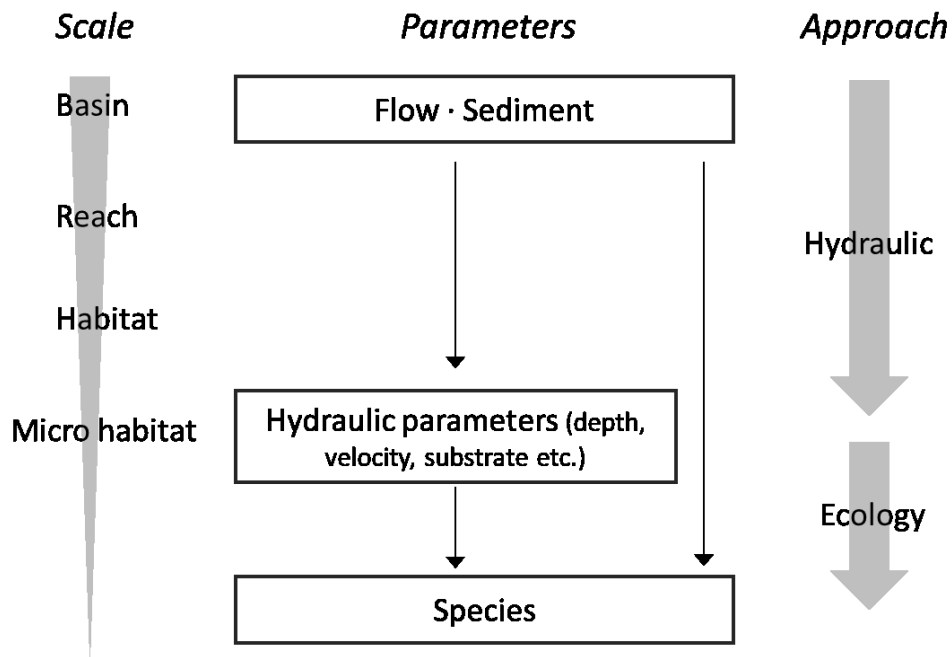


Fig. 1.1. Previous river management framework

1.1.2 New concept of river management with geomorphic habitat approaches

Recently, the importance of integrated river management with geomorphic approaches has been accepted and many researchers focus on the linkage between large-scale management activities and local ecosystem conditions. Thomson et al. (2001) emphasized that integral river management requires knowledge of how local habitat structures will respond to land- use changes or modified flow regime. Frothingham et al. (2002) said linkages between geomorphological conditions and aquatic ecosystems via the influence of fluvial processes could be helped by the management of complex fluvial systems.

A geomorphic hierarchical stream network is composed of scales of basin, segment, reach, pool/riffle and habitat (Frissell et al., 1986). Because of interdependency among the hierarchies, alternation of the basin or segment influences the reach scale, and alternation of the reach scale inherently influences pool/riffle and habitat structure. And thus, Takemon (2010) suggested that target conditions using geomorphic channel configuration could offer an appropriate framework for integrated spatial and temporal phenomena and to elucidate the links

between engineering and biology (Fig 1.2). According to habitatology (Takemon, 2010), explicit hydrogeomorphic features should be used as objective variables for hydraulic calculation in order to understand processes and mechanisms of creating and maintenance of any habitats.

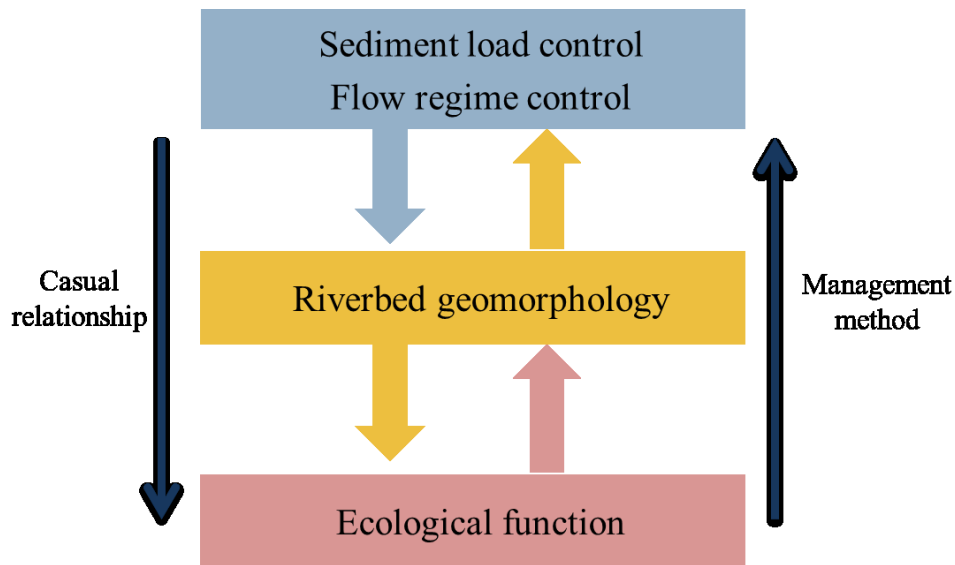


Fig 1.2 Framework in habitatology by Takemon (2007)

1.1.3 Reach-scale channel configuration (RSCC)

As a parameter of riverbed geomorphology, reach-scale channel configuration (RSCC) could be used helpfully to connect hydraulic disturbance and ecological function. Because alterations of RSCC could be predicted from knowledge of hydraulic and geomorphic conditions, it could be used as a device for linkage between ecology and hydraulics through geomorphology.

RSCC is classified into braided, meandering, anabranching or straight (Table 1.1).

Table 1.1 Description of classification of RSCC in plan view

Type of RSCC	Description
Straight	Single channel, sinuosity < 1.5 , alternating bars (Leopold and Wolman, 1957), sinuosity: 1- 1.05 (Brierley and Fryirs, 2005), width/depth ratio < 12 , sinuosity: 1- 1.2 (Rosgen, 1994)
Meandering	Single channel, sinuosity > 1.5 , dominated by suspended sediment load (Leopold and Wolman, 1957), sinuosity: 1.31- 3.0 (Brierley and Fryirs, 2005), point bar, width/depth ratio < 12 , sinuosity > 1.5 (Rosgen, 1994)
Wandering	Multiple channels, generally in gravel bed rivers (Church, 1992), number of channels: up to 3 (Brierley and Fryirs, 2005)
Braided	Multiple channels, multiple flow paths separated by transient bars (Leopold and Wolman, 1957), number of channels > 3 (Brierley and Fryirs, 2005), bed load, sinuosity < 1.3 (Schumm, 1985), width/depth ratio > 40 (Rosgen, 1994)
Anastomosing/ anabranching	Multiple channels separated by vegetated bars (Leopold and Wolman, 1957), number of channels > 3 (Brierley and Fryirs, 2005), suspended-load channel (Schumm, 1985), width/depth ratio < 40 (Rosgen, 1994)

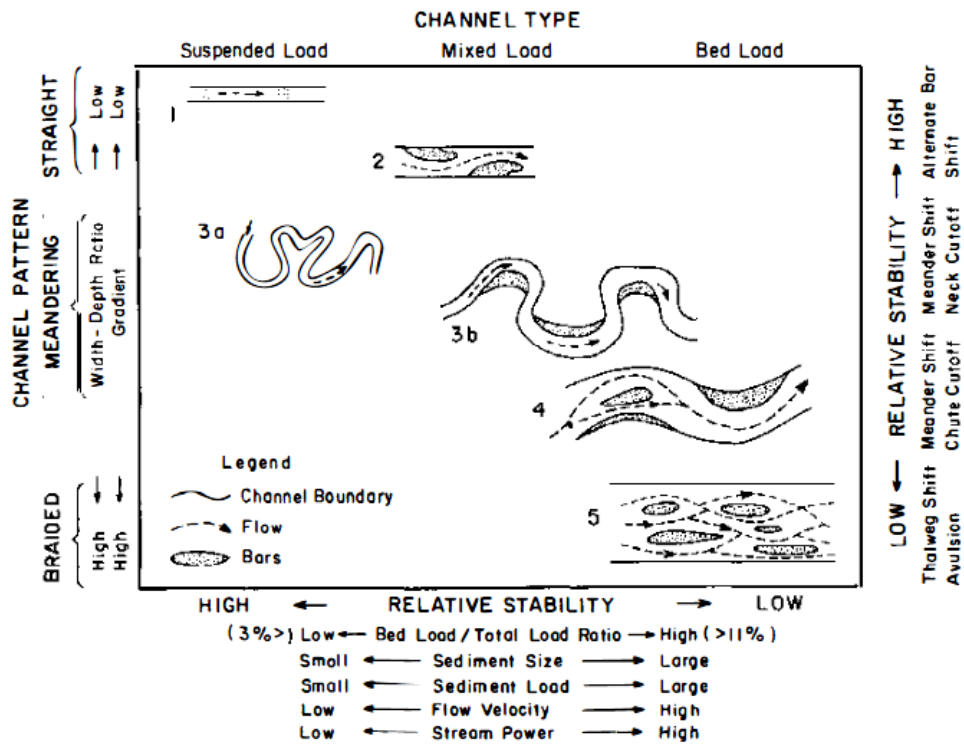
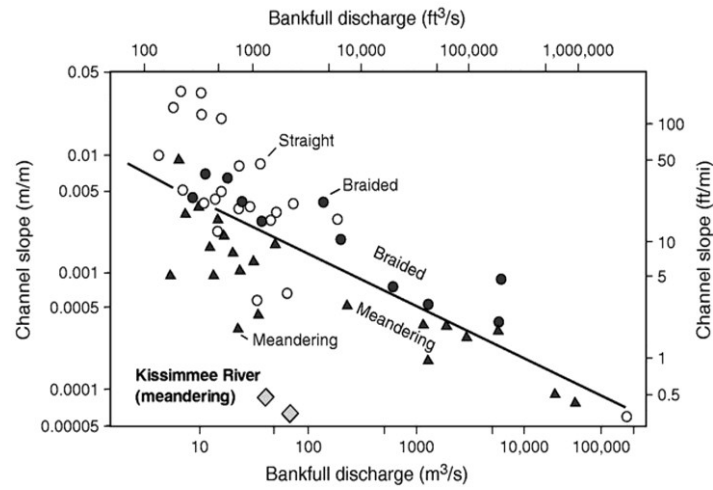


Fig. 1.3 Image of classification of RSCC by Schumm (1985)

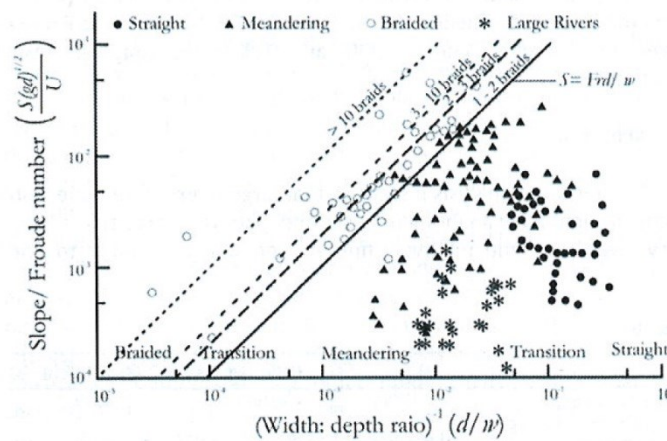
Conceptual figures for classification of RSCC have been proposed such as to Schumm (1985, Fig.1.3) and Church (1992). Schumm (1985) discussed the geomorphic- hydraulic characteristics of 5 patterns: pattern 1: straight suspended-load channel, relatively narrow and deep, low width/depth ratio; pattern 2: mixed-load straight channel, has a sinuous thalweg; pattern 3: meandering patterns; pattern 4: meander-braided transition, sediment loads are large, channel width is variable but relatively large; pattern 5: bed-load channel is a bar-braided stream.

RSCC was described in more detail by various hydrogeomorphic relationships. Leopold and Wolman (1957, Fig. 1.4a) basically discriminated straight-meandering-braided channels based on the relationship between channel slope and discharge, and these categories were theoretically related based on stream power according to Chang (1979), and slope/Froude number and width/depth ratio according to Parker (1976, Fig. 1.4b). They indicated that braided reaches (multiple flow paths separated by transient bars) taken as a whole are steeper, wider and shallower than undivided reaches. And Leopold and Wolman (1957) described that meandering channels showed sinuosity, and the ratio of thalweg length to valley length, is 1.5 or greater. Schumm and Khan (1972) also classified these categories based on relations between valley slope and sinuosity by experiment (Fig. 1.4c). Van den Berg (1995) showed braided channel and single-thread channels ($P = \text{sinuosity}$) based on relations between specific stream power and grain size (Fig. 1.4d). Muramoto and Fujita (1977, Fig 1.4e) classified RSCC into alternating bars, double row bars and braided channels based on depth-grain size ratio and width/depth ratio by flume experiment. In these simple categories, various channel types such as anastomosing, anabranching, wandering or island-braided channels were recognized. Burge (2005, Fig 1.4f) theoretically explained that anastomosed, meandering, transitional wandering and braided channels based on width/depth ratio and specific stream power. Nanson and Knighton (1996) examined character and classification of anabranching (low energy, multiple channels separated by vegetated semipermanent alluvial islands) rivers based on stream energy, and sediment size.

(a)



(b)



(c)

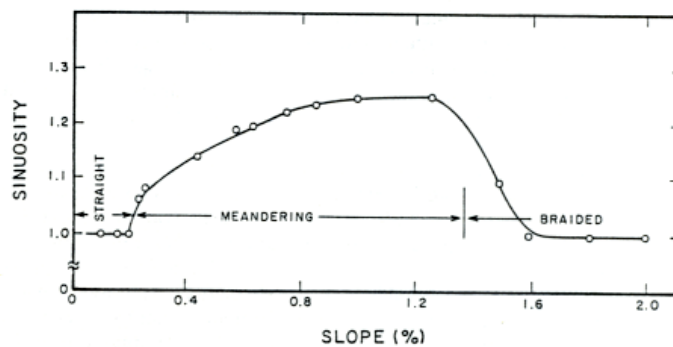
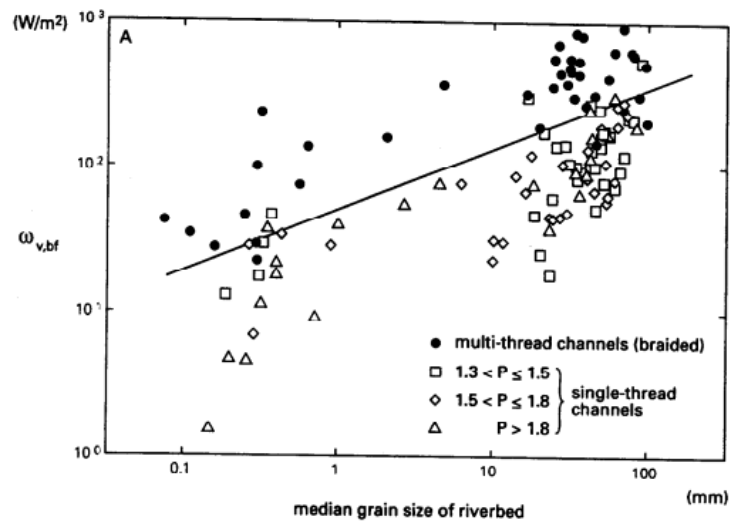
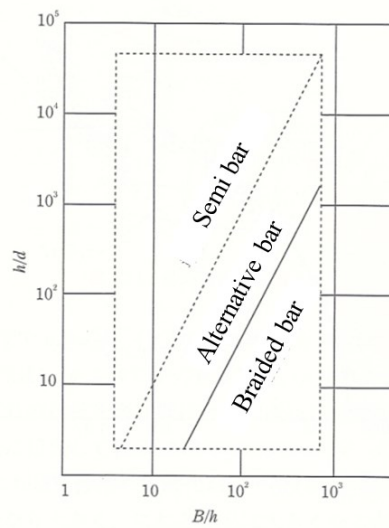


Fig. 1.4 Channel patterns (a) by slope and discharge (Leopold and Wolman, 1957) (b) by slope/Froude number and width/depth ratio (Parker, 1976) (c) by sinuosity and slope (Schumm and Khan (1972))

(d)



(e)



(f)

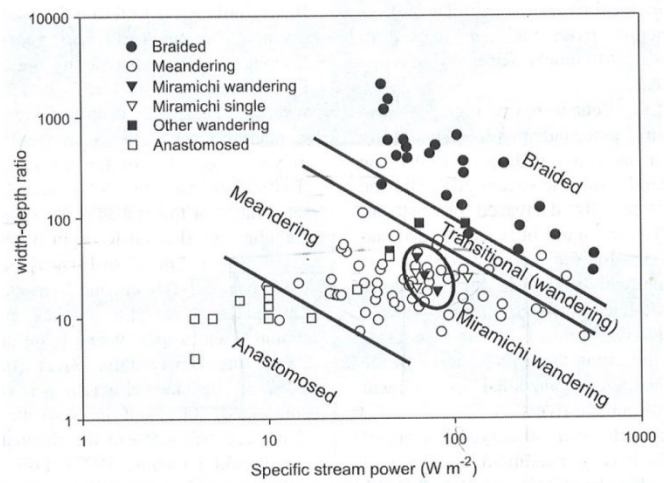


Fig. 1.4 Channel patterns (d) by stream power in bankfull discharge and grain size (Van den Berg, 1995). P =sinuosity (e) by depth/grain size ratio and width/depth ratio (Muramoto and Fujita, 1977) (f) by Width/depth ratio and specific stream power (Van den Berg, 1995; Burge, 2005)

Sometimes, these categories have been subdivided further into low-moderate sinuosity sand bed, low sinuosity fine grained channel, wandering gravel bed, etc. based on the ratio of channel abutments to valley margin, number of channels, sinuosity and geomorphic units (Brierley and Fryirs, 2005) (Fig. 1.5), and into stream type from A1a+ to G6c using the number of channels, entrenchment ratio, width/depth ratio, sinuosity, slope and bed materials (Rosgen, 1994).

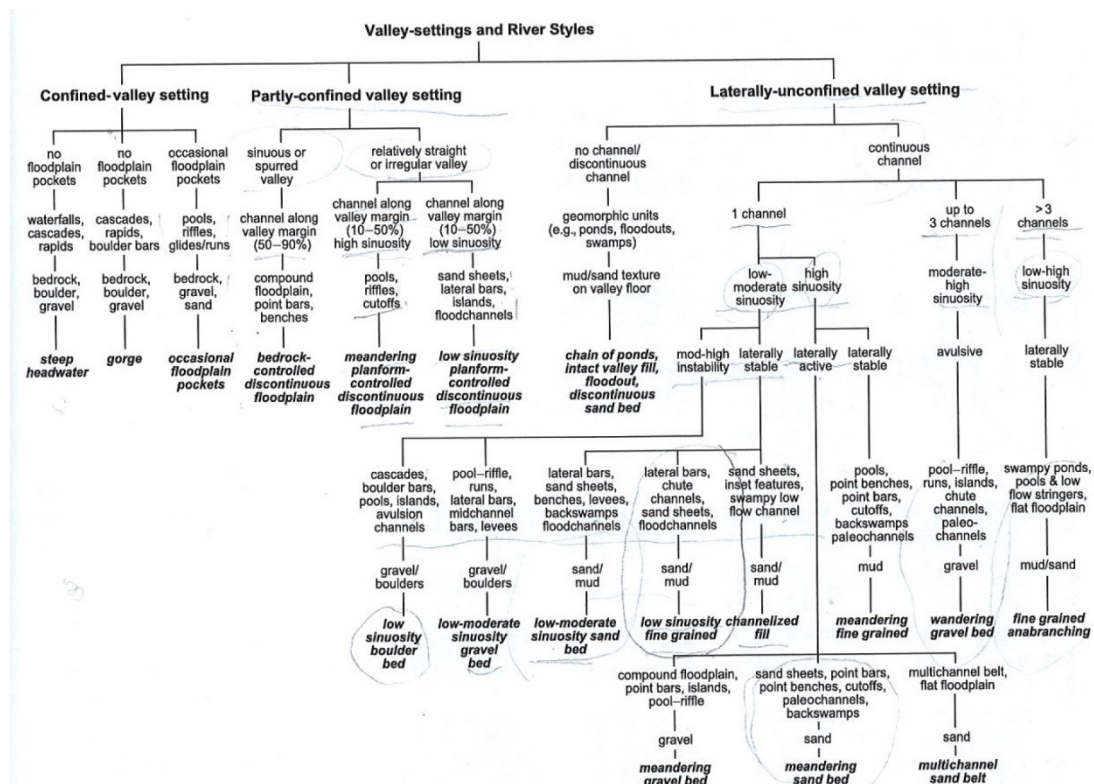


Figure 9.7 River Styles tree for a range of River Styles found in coastal NSW. Modified from Brierley et al. (2002). Reproduced with permission from Elsevier, 2003

Fig. 1.5 Classification of RSCC by Brierley and Fryirs (2005) from Brierley et al. (2002)

Since RSCC is determined and controlled by geomorphic and hydraulic characteristics, alterations of RSCC could be predicted from knowledge of hydraulic and geomorphic conditions. Therefore, if we could formulate the interrelationships among RSCC, habitat structure and ecological functions, hydrogeomorphic prediction of RSCC could be a powerful device for the prediction of changes in a river ecosystem under human impact on basin environments.

1.2 SUBJECT OF THIS STUDY

Despite a proposal of geomorphic approaches in river management (Fig. 1.2), few empirical studies exist about interrelations among ecological function, geomorphology and hydraulics. Previous studies on relations between RSCC and ecological functions have been apt to focus on particular environmental factors related to material biota such as depth and/or velocity for fish (Payne and Lapointe, 1997; Sukhodolov et al., 2009) and particulate organic matter (Ock, 2011). In those studies habitat structures are not always treated as explanatory parameters for ecological functions, although they are closely related to species diversity, and can be easily detected even in aerial photos. Apart from relations with RSCC, there have been a lot of works on geomorphic habitat structures for aquatic fauna. For example, Gordon et al. (2004) mentioned that riffles tend to support high densities of benthic invertebrates and are thus important as food-producing areas for benthivorous fish. Scott and Nielsen (1989) detected that backwater is crucial for the maintenance of nest-building fish. In order to formulate the interrelationships among RSCC, habitat structure and ecological functions, we need to investigate relations between RSCC variations and the habitat structure. Some studies examined relations between RSCC and specific lotic habitat structure. Lofthouse and Robert (2008) noted riffle-pool sequence increased through meander development. Brierley and Fryirs (2005) also explained that pools tend to occur at characteristic locations, typically along the concave bank of bends in sinuous alluvial channels. In terms of location of habitat structure, Brierley and Fryirs (2005) noted that ridges (ponds) formed downstream

of vegetation or other obstructions on point bars, and chute channels (similar bar-head wando) initiated at the head of point bars. Thus, few researchers have addressed the relations between RSCC and habitat structure.

This study focuses on geomorphic lotic and lentic habitat structure as well as biodiversity of fauna as ecological functions. We try to develop methods for integrated riverbed management through the evaluation of geomorphic RSCC in relation to habitat structure and biodiversity as ecological functions, empirically using these relationships. The purposes of this study are 1) to present empirical relations between RSCC and habitat structure using historical data on the riverbed geomorphology, 2) to demonstrate relations among aquatic habitat structures and species richness and/or fish and mussels and 3) to propose an ecological evaluation method of RSCC for integrated riverbed management.

1.3 INTRODUCTION OF THE KIZU RIVER

The study area was established in the lower reaches (0~26 km) of the Kizu River, a tributary of the Yodo River in central Japan (Fig. 1.6). The Kizu River is a typical sandy river derived from weathered granite in the upper stream (Ito et al, 2011), a basin with an area of 1,596 km². A total of 5 dams, Takayama Dam (constructed in 1969), Syourenji Dam (1970), Murou Dam (1974), Nunome Dam (1992), and Hinachi Dam (1999), are located in the basin.

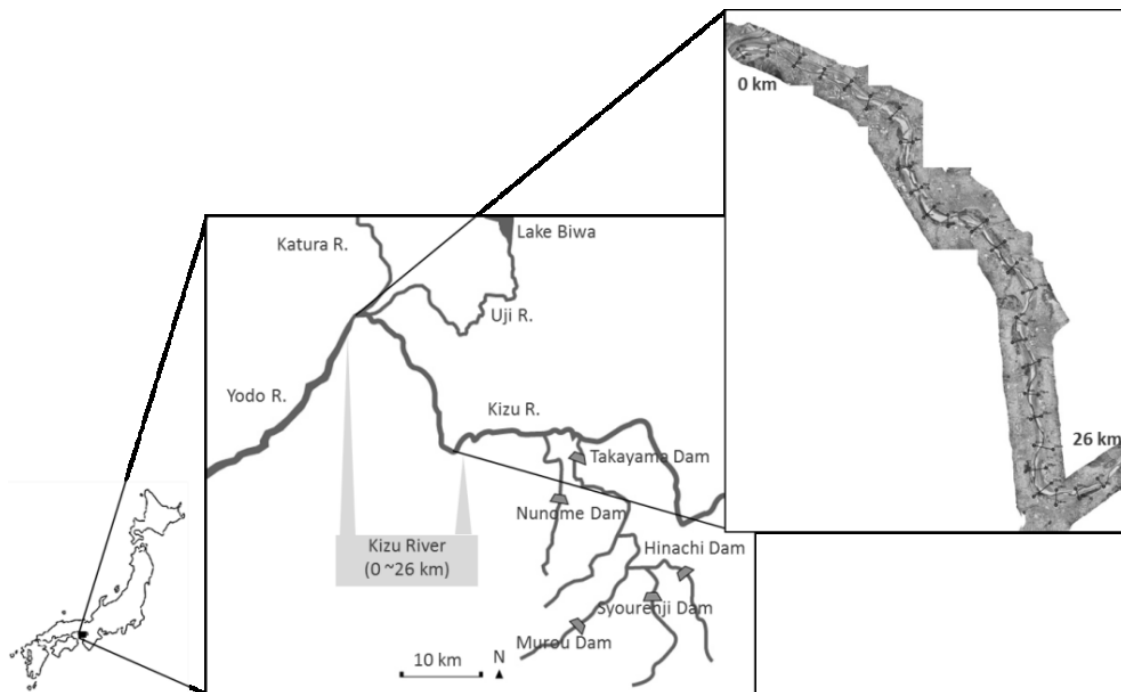


Fig. 1.6 A map of the Kizu River basin

Egashira (2000) calculated the volume of sediment transport in the Kizu River and results showed significant and consistent decreases after dam construction (Fig 1.7). According to the Kizu River Research Group (2003), braided channels in the 1960s changed to channels having alternative bars after dam construction and sand excavation. Takebayashi et al. (2002) studied temporal and spatial variation characteristics of braided streams by flume experiments and numerical simulation.

Due to sediment reduction resulting from the dam construction and sand excavation between 1958 and 1963, riverbed degradation was accelerated and had continued in the lower reach (0 – 10 km) until now (Ashida et al., 2008). On the other hand, the water capacity of the dam decreased by the deposition of sediment in the dam reservoir (Kantoush et al., 2010).

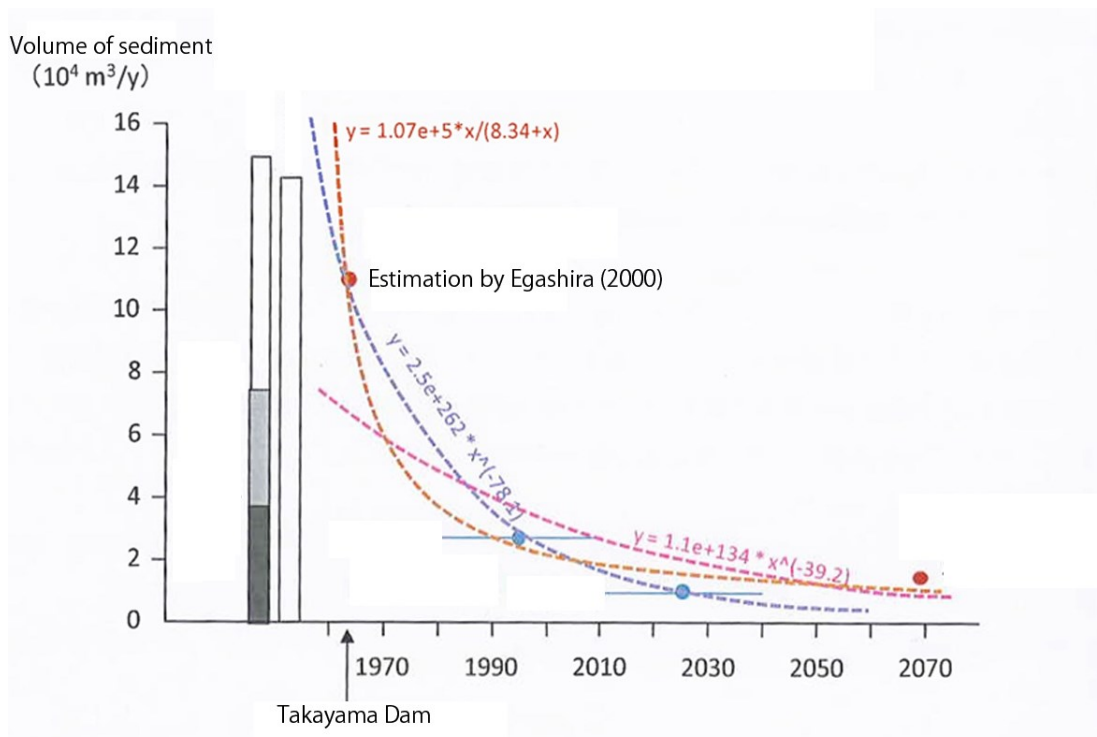


Fig. 1.7 Evaluated volume of sediment transport by Takemon etl al., (2013)

Reduction of the peak discharge and sediment supply resulted in an expansion of vegetation including woodland on the active channel and islands as well as on the terrace (Kizu River Research Group, 2003, Fig 1.8). The Kizu River Research Group (2003) explained the processes of riverbed degradation, focusing on vegetation expansion on bars between 0 and 18 km. Vegetation expansion seems to affect riverbed degradation due to flow concentration onto the riverbed, and to influence increasing bar height due to the deposition of small particles on vegetated bars. Some studies with ecological approaches were investigated by Obana and

Tsujimoto (2009) and Yamagishi et al. (2009). They indicated the importance of ecological functions of sand bars using micro-landscapes (Obana and Tsujimoto, 2009) and sympatric species of plovers (Yamagishi et al., 2009)

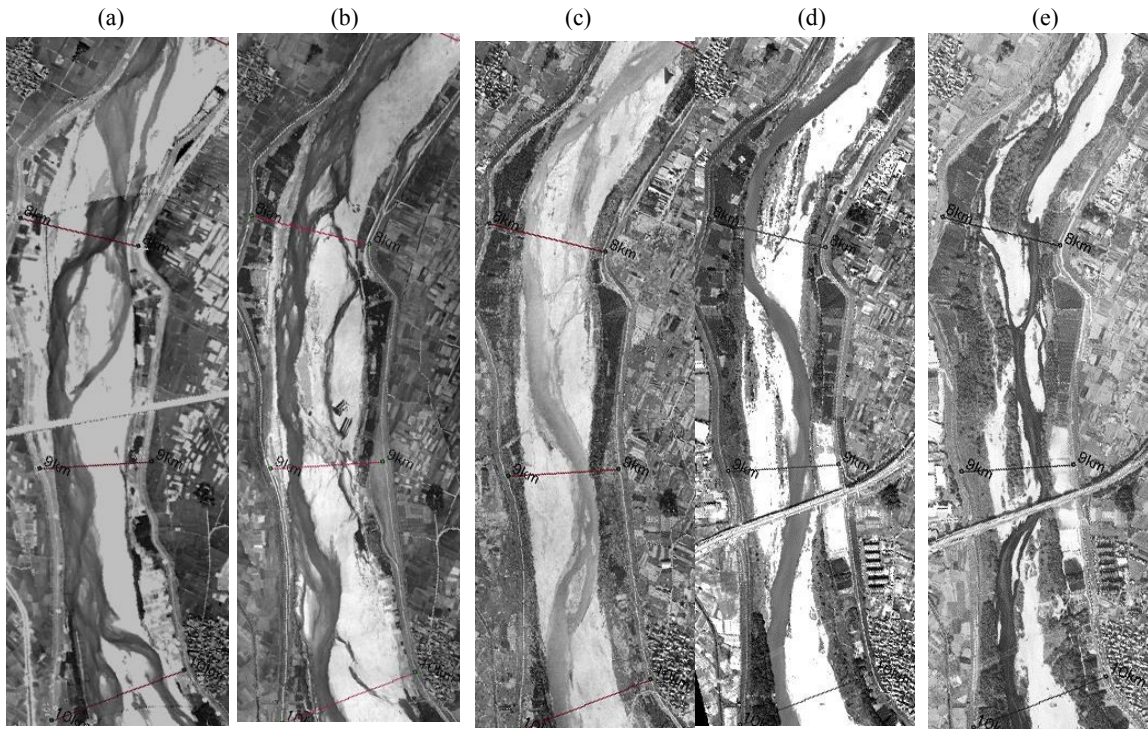


Fig. 1.8 Historical changes in (a) 1948 (b) 1961 (c) 1971 (d) 1990 (e) 2010 between 7-10 km

1.4 CHAPTER OUTLINE

The following 4 researches were performed for the purposes shown in Fig. 1.9

In chapter 2, relations between aquatic habitat structure and RSCC, and those between RSCC and disturbance regimes were investigated using 9 sets of aerial photos and cross-sectional measurements taken in the past 65 years from 1948 to 2012 in the lower reaches of the Kizu River. A total of 8 RSCC types were classified based on reach-scale geomorphological parameters: single; slightly wandering straight and sinuous; quite wandering straight and sinuous; bifurcated wandering straight and sinuous; and braided channels. Aquatic habitats were classified into 4 lotic habitats (main-slow, secondary-slow, gently bending riffle, sharply bending riffle) and 4 lentic habitats (bar-head wando, bar-tail wando, active pond, terrace pond), and their diversity indices (richness, evenness, diversity, soundness) were analyzed in relation to RSCC types. The relations of RSCC types to disturbance regimes also were analyzed.

In chapter 3, relations among the abundance of bitterling and mussel communities, habitat structures and RSCC were described. A total of 120 ponds on the lateral bars and terraces were monitored regarding fish and mussel communities and habitat conditions in 2007 and 2010. These ponds were classified into bar head-active pond (BH-AP), bar head-terrace pond (BH-TP), bar tail-active pond (BT-AP) and bar tail-terrace pond (BT-TP). Flooding frequency was used as a key parameter reflecting habitat conditions for bitterlings and mussels, and floodplain vertical shape index (FVSI) was used as characteristic of RSCC. FVSI was evaluated by the number of habitat structures having suitable flooding frequency using data in 2007 and 2010, and they were connected with long-term changes of FVSI to evaluate historical changes in potential habitat suitability for bitterlings and mussels.

In chapter 4, the historical influence of the past environmental conditions on the present richness of species in lentic habitats was shown. Richness of fish, bitterlings and mussels in lentic habitats (active pond and terrace ponds) were analyzed to not only present environmental habitat conditions but also the past conditions in lentic

habitat structures using a principal component analysis (PCA) and a generalized linear model (GLM).

In chapter 5, the evaluated RSCC in relation to habitat structure and bitterlings/mussels was summarized, and an ecological evaluation method of RSCC for riverbed management in the Kizu River was proposed.

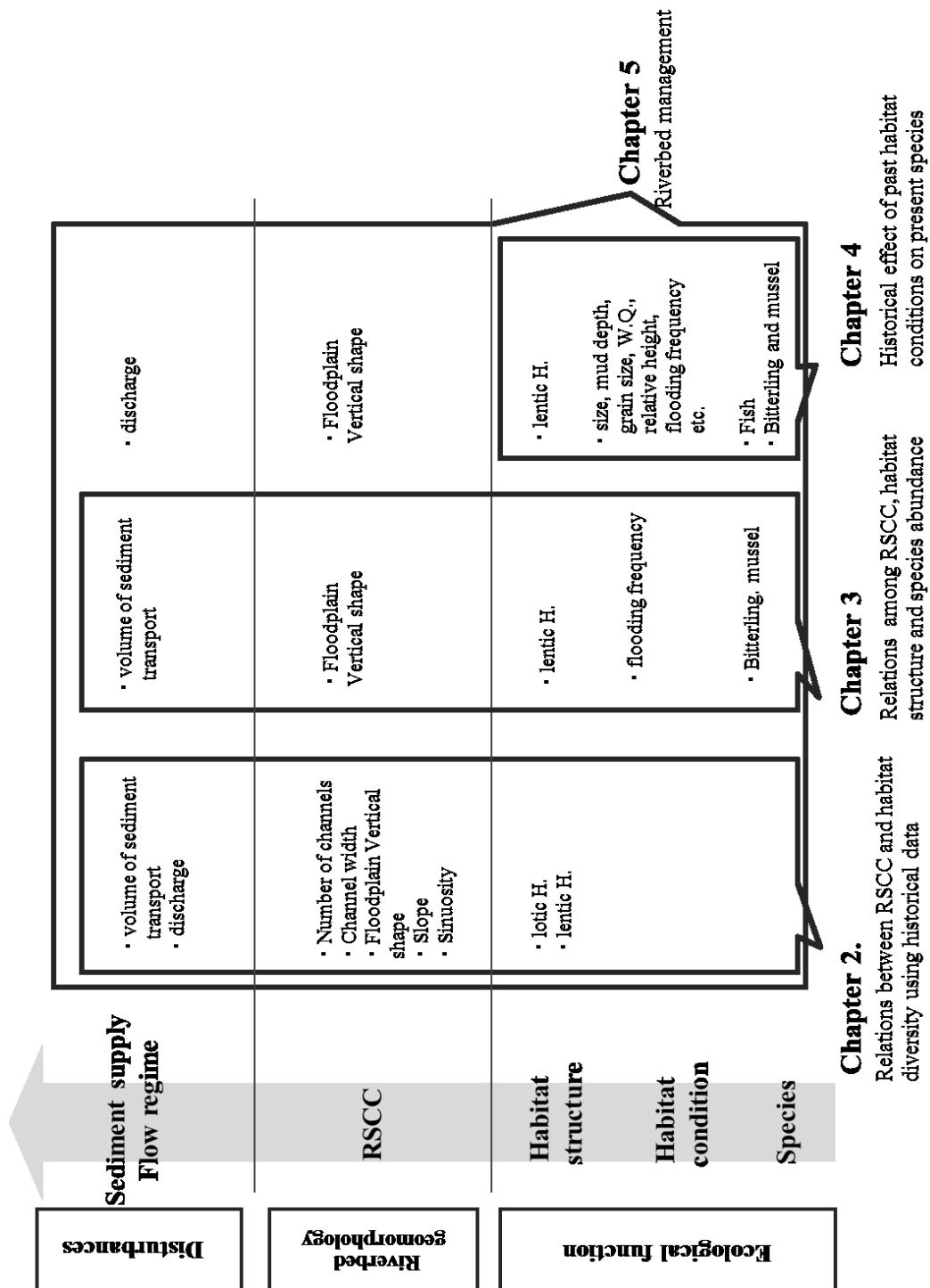


Fig. 1.9 Chapter outline

Chapter 2. Relations of reach scale channel configuration (RSCC) to habitat structure

ABSTRACT

Relations between aquatic habitat structure and reach-scale channel configuration (RSCC), and those between RSCC and disturbance regimes were investigated using 9 sets of aerial photos and cross-sectional measurements taken in recent 65 years from 1948 to 2012 in the lower reaches of the Kizu River, a tributary of the Yodo River in Japan. A total of 8 RSCC types were classified based on reach-scale geomorphological parameters: single, slightly wandering straight and sinuous, quite wandering straight and sinuous, bifurcated wandering straight and sinuous, and braided channels. Aquatic habitats were classified into 4 lotic habitats (main-slow, secondary-slow, gently bending riffle, sharply bending riffle) and 4 lentic habitats (bar-head wando, bar-tail wando, active pond, terrace pond), and their diversity indices (richness, evenness, diversity, soundness) were analyzed in relation to RSCC types. The results showed that braided channels had the maximum habitat abundance with the highest number of bar-tail wando and lotic habitats. Quite

wandering-straight channels had the maximum habitat diversity, and bifurcated wandering sinuous channels had the maximum habitat soundness. Analyses on the relations of RSCC types to disturbance regimes showed that the number of braided channels and bifurcated wandering sinuous channels increased with increasing volume of sediment transport and the maximum discharge, whereas the number of quite wandering-straight channels reached the maximum at around 40,000-60,000 m³/yr in the volume of sediment transport, indicating that higher level of disturbance realizing at least 40,000-60,000 m³/yr in the volume of sediment transport is required for restoration of habitat structure in the Kizu River

2.1 INTRODUCTION

RSCC such as braided, meandering, wandering, or anastomosing and straight channels can be classified by hydraulic-geomorphic parameters such as discharge and slope (Leopold and Wolman, 1957), depth-grain size ratio and width-depth ratio (Muramoto and Fujita, 1977), sediment load and lateral stability (Schumm, 1985). Sometimes, these broad categories have been subdivided further into low-moderate sinuosity sand bed, low sinuosity fine grained channel, wandering gravel bed, etc. based on ratio of channel abutments to valley margin, number of channels, sinuosity and geomorphic units (Brierley et al., 2002), and stream type from A1a+ to G6c using number of channels, entrenchment ratio, width/depth ratio, sinuosity, slope and bed materials (Rosgen, 1994). Furthermore, braided channels and/or meandering channels having alternative bars had been explained by depth-grain size ratio and width-depth ratio using flume experiment (Muramoto and Fujita, 1977). These distinctive relations of RSCC patterns to hydraulic parameters indicate that we could predict changes in RSCC patterns from both empirical and computational data on hydraulic and geomorphic conditions including flow regimes (Tiegs and Pohl, 2005; Winterbotton, 2000), sediment supply (Draut et al., 2011), and direct human impacts such as sediment excavation and channelization (Surian and Rinaldi, 2003).

A hierarchical stream network is composed of scales of basin, segment, reach, pool/riffle and habitat (Frissell et al., 1986). Because of interdependency among the

hierarchies, geomorphic alternation of RSCC inherently influences pool/riffle and habitat structure. On the other hand, ecological characteristics of streams such as flora and fauna, biodiversity, and productivity are closely related to the reach scale geomorphology (Takemon, 1997). As most stream animals need a set of different habitats in different stages of their life cycles, such as deep-slow for feeding, backwater for resting, and gravel bars for spawning of some fish (Holomuzki and Messier 1993) and invertebrates (Yuma and Hori 1990). Thus, 'habitat heterogeneity hypothesis' (Simpson, 1949) states that an increase in the number of habitats and/or an increase in their structural complexity leads to increased species diversity. Therefore, if we could formulate the interrelationships among RSCC, habitat structure and ecological functions, hydro-geomorphic prediction of RSCC could be a powerful device for prediction of changes in a river ecosystem under human impacts on basin environments.

However, previous studies on relations between RSCC and ecological functions have apt to focus on particular environmental factors such as depth and/or velocity for fish (Payne and Lapointe, 1997; Sukhodolov et al., 2009). In those studies habitat structures are not always treated as explanatory parameters for ecological functions, although they are closely related to species diversity, and can be easily detected even in aerial photos. Apart from relations with RSCC, there have been a lot of works on geomorphic habitat structures for aquatic fauna. For example, Gordon et al. (2004) mentioned that riffles tend to support high densities of benthic invertebrates, and are thus important as food-producing areas for benthivorous fish. Scott and Nielsen (1989) detected that backwater is crucial for the maintenance of nest-building fish. In order to formulate the interrelationships among RSCC, habitat structure and ecological functions, we need to investigate relations between RSCC variations and the habitat structure at the same time.

Thus, this study elucidates relations between hydro-geomorphology and geomorphic habitat structure in order to understand geomorphic processes and to develop method of river management in basin scale. Recently importance of integrated river management with geomorphic approaches has been accepted and many researcher focus on linkage between large scale management activities and

local ecosystem conditions. Thomson et al. (2001) emphasized that integral river management requires knowledge of how local habitat structures will respond to land-use changes or modified flow regime. Frothingham et al. (2002) said linkages between geomorphological conditions and aquatic ecosystems via the influence of fluvial processes could be helped by the management of complex fluvial systems. And then, Takemon (2010) suggested that target conditions using geomorphic channel configuration could offer an appropriate framework for integrated spatial and temporal phenomena and to elucidate the links between engineering and biology. However, despite of this conceptual framework, in fact, both empirical and theoretical studies have been limited and have been not well documented. Only few researchers studied relations between habitat structures and flow regimes based on specific geomorphological conditions such as braided channel; e.g. relations between habitat dynamics (low age) and flooding in a braided river (Dave et al., 2002), and composition of habitat structures by flood pulse in braided flood plains (Van der nat et al., 2003). Thus, in order to establish an appropriate method for the integrated river management, relations between RSCC and habitat structures should be empirically well defined.

This paper aims at revealing relationships among RSCC types, habitat structure and disturbance regimes in terms of maximum discharge, annual sediment discharge, flood frequency and flood duration. By showing these relationships it is expected to know disturbance regimes required for creating the maximum habitat diversity. In this study, we tried to link local (habitat structure), reach (RSCC) and basin scales (volumes of sediment transport and flooding) with an interdisciplinary approach using historical data. The investigation was conducted on the Kizu River located in central Japan, where riverbed degradation and vegetation expansion proceeded after dam construction and sand excavation over a 65-year period. We discuss the appropriate target image of RSCC in terms of habitat structures in the Kizu River and its application to riverbed management in the basin scale.

2.2 METHODS

2.2.1 Study area

The study area was established in the lower reaches (0~26 km) of the Kizu River, a tributary of the Yodo River in central Japan (Fig. 1.1). The peak discharge of the river is caused by seasonal typhoons in summer and autumn. The largest flood event occurred in 1959 and reached almost 6000 m³/s, whereas intensity of peak discharge decreased by about 3,000m³/s after the dam construction (Fig. 2.1a). The annual mean discharge is about 25 m³/s and high discharge is about 43 m³/s. The annual mean bed-load transported to the lower reach was estimated to be about 183,000m³/y in the 1960's, but about 23,000 m³/y in the 2000's (Ashida et al., 2008). The channel width of the study area was 300 – 500 m (partly about 800 m) and fine bed materials (<16 mm) dominated (Kobayashi and Takemon, 2013) with a mean grain size of 4.27 cm (Ashida et al., 2008). Due to sediment reduction resulting from the dam construction and sand excavation between 1958 and 1963, riverbed degradation was accelerated and had been continued in the lower reach (0 -10 km) until now (Ashida et al., 2008). In addition, reduction of peak discharge and sediment supply resulted in an expansion of vegetation including wood-land on the active channel and islands as well as on the terrace (Kizu River Research Group, 2003). To prevent the over-expansion of wood-land, a wood cutting project was undertaken by the Yodo River bureau between 2009 and 2011.

2.2.2 Materials

Aerial photos taken by the Yodogawa River Bureau between 1948 and 2012 were used to examine long-term changes in RSCC and habitat structures in the Kizu River. The orthorectified and georeferenced photos taken in 1948, 1961, 1971, 1979, 1990, 2002, 2006, 2010 and 2012 were compiled and overlaid sequentially using ArcView (Version 10, ESRI). All aerial photos were taken during low water depth periods except the photo from 1990, which was taken in the typhoon season (about 0.1 m higher than normal water level, Fig. 2.1b). Cross-section measurement data from 1965, 1971, 1980, 1990, 2001, 2006 and 2010 were used and matched with the

aerial photos. We divided the study area into 2 km units according to the mean wavelength of alternative bars (mean wavelength: 1.93 km, range: 1.6 - 2.6 km, Table. 2.5).

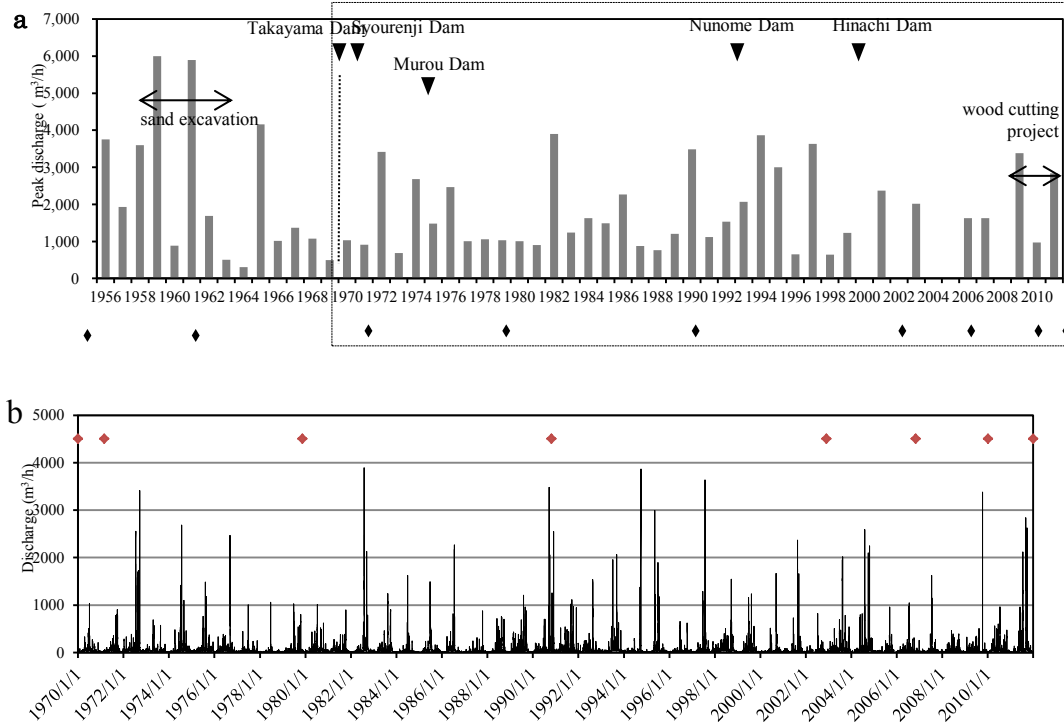


Fig. 2.1 Historical changes of discharge; (a) annual peak discharge from 1956 to 2011, and (b) hourly discharge from 1970 to 2012 at Inooka station (16 km from conjunction) in the Kizu River.

◆ denotes data taken from aerial photos

Discharge data consist of the annual peak discharge from 1956 to 2011 and the hourly discharge data from 1970 to 2011, as measured by the Japan metrological agency and the Yodogawa River Bureau. According to Ashida et al. (2008), mean grain size is 4.27 cm and the highest grain size is 9.5 cm in the Kizu River, and their threshold discharges are 1740 m³/s and 3000 m³/s respectively. Thus, we measured the number of flood events and durations (hours) exceeding 1740 m³/s (F_{n1740} , F_{t1740}) and 3000 m³/s (F_{n3000} , F_{t3000}). Additionally, flood events and durations per year also were used. All discharge data (maximum, event number, duration) were measured by flood events occurring during periods between the taking of a previous aerial photo

and a target year (Table 2.1). Data on annual sediment transport was referred to the values estimated by Egashira et al. (2000). Annual sediment transport and maximum discharge indicated intensity of disturbance, and number of floods and durations meant frequency of disturbance.

Table 2.1 Historical changes of flow regime and annual sediment transport of the Kizu River between 1961 and 2012

	1961	1971	1979	1990	2002	2006	2010	2012
Q _{max} (m ³ s ⁻¹)	6,000.	4,161.9	3,413.2	3,895.1	3,634.9	2,589.2	3,376.3	2,838.8
Fn ₃₀₀₀	5 (0.38)	2 (0.2)	1 (0.11)	2 (0.18)	2 (0.17)	0 (0)	1 (0.25)	0 (0)
Fn ₁₇₄₀			5 (0.56)	4 (0.36)	7 (0.58)	4 (1.0)	1 (0.25)	3 (1.5)
Ft ₃₀₀₀ (hour)			5 (0.56)	13 (1.18)	13 (1.08)	0 (0)	4 (1.0)	0 (0)
Ft ₁₇₄₀ (hour)			41 (4.56)	79 (7.18)	56 (4.67)	22 (5.5)	11 (2.75)	39 (19.5)
Annual sediment transport (m ³ /y)	10057 8.2	79253. 7	55511. 5	37444. 4	24337. 7	20025. 0	17137. 9	15856. 2

Q_{max}, Fn (flood event), Ft (flood duration) were measured flood event occurred during periods between the taking of a previous aerial photo and a target year. Values in parenthesis indicated number and duration of flood event per year.

2.2.2 Parameters of RSCC

A total of 6 reach-scale geomorphological parameters were used to show conditions of the reach-scale channel configuration in Table 2.2. Number of channels, sinuosity, channel width, and landscape composition were measured using aerial photos, and floodplain vertical shape index (FVSI) and bed slope were calculated using cross-section data. FVSI was defined as a degree of convex or concave shape in the altitude distribution of the floodplain (Takemon et al., 2013, Fig. 2.2); i.e. positive values of FVSI are reflected in a convex vertical shape, and the negative values in a concave vertical shape. In the aerial photos, texture, shape

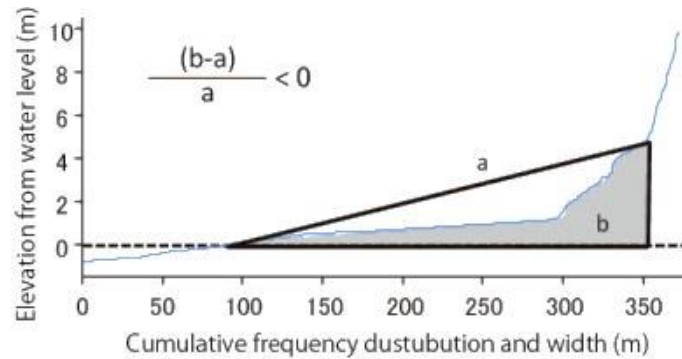
and shadows were used to detect active channels, terraces with bush-land and wood-land. Channel width was defined as the width of active zone between both ends of bare-land including water surface (Hohensinner et al., 2011).

Table 2.2 Parameters of RSCC measured using aerial photographs and cross-section data in the Kizu River. All the parameters were measured per 2 km unit.

Parameters	Definition	Reference
Number of channels	Average number of flow channels by 10 transects with 200 m intervals	Howard et al. (1970)
Sinuosity	Ratio of the main flow channel length to valley length	Leopold and Wolman (1957)
Channel width	Average width of active channel zone by 10 transects with 200 m intervals	Hohensinner et al. (2011)
Floodplain vertical shape index (FVSI)	Difference of integral values of relative elevation of riverbed to normal water level and those of uniformly distributed elevation within a 2 km unit	Takemon et al. (2013)
Landscape composition	Ratio of wood-land, bush-land, bare-land and water-surface area to the total area of the reach	Present study
Bed slope	Ratio of fall (height) to distance along the channel	Gordon et al. (2004)

In order to define the condition of RSCC, ‘channel types’ were classified based on a set of geomorphological parameters. According to Choi et al. (2013) and Takemon et al., (2013), the number of channels, channel width, FVSI and landscape composition continuously decreased or increased during 65 years, whereas sinuosity and bed slope did not significantly differ during the same period. Thus, among temporal-change parameters, the number of channels was used representatively for classification of channel types, and among spatial-change parameters, sinuosity was used (Table 2.3).

Concave shape



Convex shape

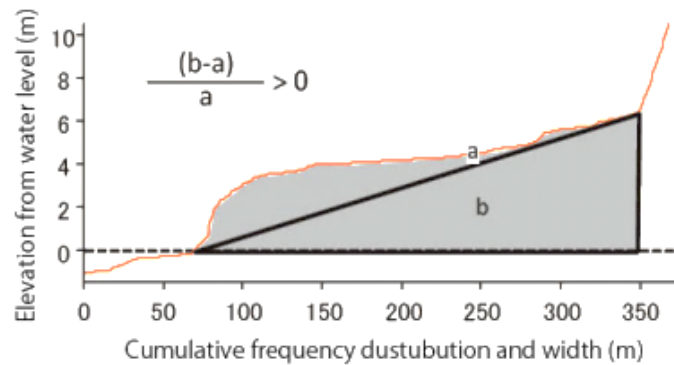


Fig. 2.2 Image of Floodplain Vertical Shape Index (FVSI)

We divided channel types into 8 categories to show more detailed conditions in the Kizu River (Table 2.3, Fig. 2.3). Number of channels was classified into single, wandering (CN up to 3) and braided (CN>3) by Brierley and Fryirs (2005). The wandering channel (CN up to 3) was divided into 3 groups (slightly, quite and bifurcated wandering channels), because most of the reaches of the Kizu River were included in these channel types. Sinuosity was classified into straight ($S < 1.05$), sinuous ($1.05 \leq S < 1.3$) and meandering ($1.3 \leq S$) according to Schumm (1985). Wandering channels with a number of channels between 2.5 and 3 ($2.5 \leq CN < 3$) were included in braided channel (CN>3). Since single and braided channels had just the sinuous type, we addressed them as single and braided channels without the

use of the word ‘sinuous’. A total of 116 reaches were divided into 8 channel types during 1948-2002.

Table 2.3 Classification of channel types in the Kizu River

Number of channels		Sinuosity	Channel types			Abbr.
Single	CN<1.2	$1.05 \leq S$	Single sinuous channel			Ssi
	$1.2 \leq \text{CN} < 1.5$	$S < 1.05$	Slightly wandering straight channel			SWst
		$1.05 \leq S$	Slightly wandering sinuous channel			SWsi
Wandering	$1.5 \leq \text{CN} < 2.0$	$S < 1.05$	Quite wandering straight channel			QWst
		$1.05 \leq S$	Quite wandering sinuous channel			QWsi
	$2.0 \leq \text{CN} < 2.5$	$S < 1.05$	Bifurcated wandering straight channel			BWst
		$1.05 \leq S$	Bifurcated wandering sinuous channel			BWsi
Braided	$2.5 \leq \text{CN}$	$1.05 \leq S$	Braided sinuous channel			Bsi

Sinuosity: $S < 1.05$ (straight), $1.05 \leq S$ (sinuous)

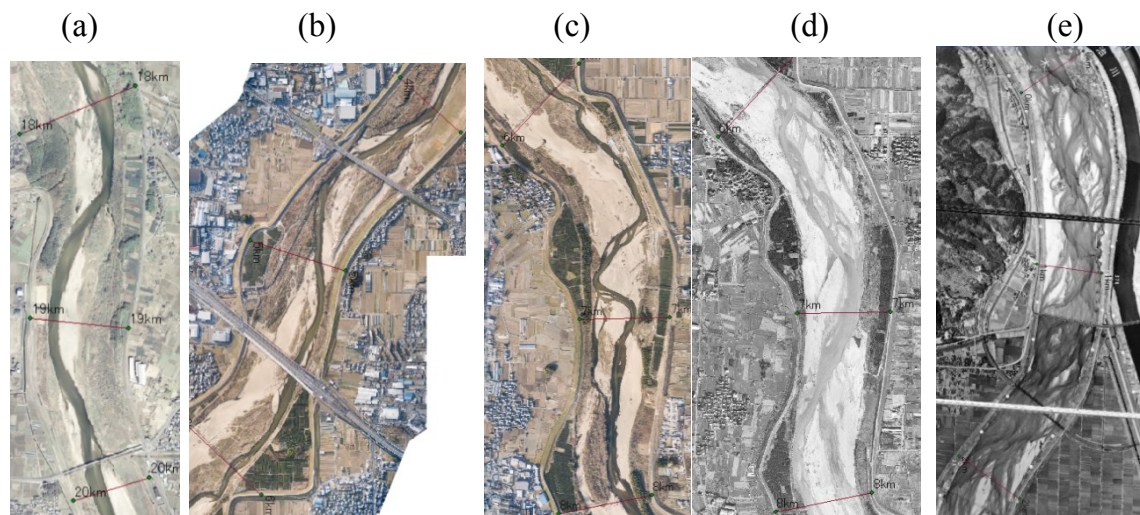


Fig. 2.3 Image of channel patterns; (a) Ssi (18-20 km in 2012) (b) SWsi (4-6 km in 2010) (c) QWsi (6-8 km in 2010) (d) BWsi (6-8 km in 1971) (e) Bsi (0-2 km in 1948)

2.3.3 Classification of habitat structures

Habitat types were classified using aerial photos in Table 2.4 according to Takemon (2010). According to previous studies on invertebrate communities (Kobayashi and Takemon, 2013) and on particulate organic matter distribution (Nakai, 2012), the angle of riffle flow direction to channel direction influenced the biomass and community compositions. Thus, riffles were divided into two types, gently bending riffle and sharply bending riffle, on the basis of Kobayashi and Takemon (2013), and thus a total of 8 habitat types were used. We measured the number of each habitat type to determine their abundance. At the same time, the area of habitats also was calculated. All aquatic habitats having water-surface in channels and bars were measured. Diversity indices, e.g., habitat richness, evenness index, diversity index and soundness index were calculated for each 2 km unit. The habitat richness was defined as the total number of aquatic habitat types. The habitat diversity index was calculated using the Shannon-Wiener index (H').

$$H' = -\sum_{i=1}^R p_i \log p_i$$

Here, P_i is the proportional abundance of the i th type, and R is the richness of habitat types

Habitat evenness index was measured using Pielou's index (J').

$$J' = \frac{H'}{\ln S}$$

Here, H' is the Shannon-Wiener diversity index and S is the habitat richness.

Habitat soundness index was made by combination of abundance of total habitats and habitat diversity index. Values of number of total habitats and habitat diversity index within 2 km unit were transferred from minimum 0 to maximum 1 respectively, and they were multiplied in each unit.

Table 2.4 Classification of aquatic habitats based on aerial photographs in the Kizu River

Habitat type			Description
Lotic	Slow	Main-slow	Slow flow with smooth water surface located between riffles in the main channel
		Secondary-slow	Slow flow with smooth water surface located between riffles in the secondary channel
	Riffle	Gently bending riffle	Shallow flow with rough water surface overflowing a lateral bar with a bending angle smaller than 30°
		Sharply bending riffle	Shallow flow with rough water surface overflowing a lateral bar with a bending angle larger than 30°
Lentic	Wando	Bar-head wando	Lentic water located at the bar head opening to the channel
		Bar-tail wando	Lentic water located at the bar tail opening to the channel
	Pond	Active pond	Isolated lentic water on the low flood plain
		Terrace pond	Isolated lentic water on the terrace

2.3.4 Statistical analyses

Historical changes of parameters and relations of habitat structures to channel types were compared using one-way ANOVA with a post-hoc test by Turkey-HSD. Since the area of habitats mainly depended on the ratios of water-surface (in landscape composition), they were only used to show historical changes. To know how channel types reflected the intensity and frequency of disturbances, relations of the number of each channel type per year to disturbance regimes (annual sediment transport, Q_{\max} , F_{n3000} , F_{n1740} , F_{t3000} , F_{t1740} per year) were analyzed using regression analysis. An α value of 0.05 was used to indicate statistical significance for all tests. Statistical analyses were performed using SPSS software (release 19, SPSS Inc.).

Table 2.5 Historical changes in habitat structures and reach-scale geomorphological parameters (mean \pm standard error) in the Kizu River between 1948 and 2012. All the parameters were measured per each 2 km reach. Number of reaches measured: n=13 except for 1961 (n=12)

	1948	1961	1971	1979	1990	2002	2006	2010	2012
Habitat structures									
Abundance of 8 habitats (n)	47.9 \pm 18.8 ^{ab}	58.1 \pm 9.4 ^a	50.5 \pm 16.7 ^{ab}	43.5 \pm 9.9 ^{ab}	33.7 \pm 6.9 ^b	40.2 \pm 11.2 ^b	38.8 \pm 9.7 ^b	47.8 \pm 18.6 ^{ab}	45.2 \pm 14.9 ^{ab}
Area of 8 habitats ($\times 10^4$ m ²)	31.7 \pm 11.2 ^a	26.8 \pm 5.7 ^{ab}	23.6 \pm 4.4 ^{bc}	17.0 \pm 2.6 ^{de}	19.2 \pm 3.5 ^{cd}	13.9 \pm 12.3	13.5 \pm 2.5 ^{de}	11.5 \pm 1.7 ^{de}	16.6 \pm 2.6 ^{de}
de									
Number of main slow	4.2 \pm 2.2 ^c	5.3 \pm 2.0 ^{abc}	6.0 \pm 0.7 ^{ab}	5.1 \pm 0.9 ^{abc}	4.6 \pm 0.7 ^{bc}	5.7 \pm 1.3 ^{abc}	6.5 \pm 1.0 ^a	5.9 \pm 1.4 ^{ab}	5.5 \pm 1.3 ^{abc}
Number of secondary slow	6.2 \pm 4.5	5.9 \pm 1.2	6.5 \pm 2.5	5.5 \pm 2.5	3.7 \pm 2.5	6.6 \pm 2.8	5.0 \pm 3.1	6.3 \pm 4.5	5.0 \pm 4.3
Number of gently bending riffle	8.7 \pm 7.2 ^a	3.6 \pm 1.8 ^b	3.1 \pm 1.5 ^b	2.6 \pm 1.3 ^b	2.4 \pm 1.4 ^b	2.8 \pm 1.7 ^b	3.4 \pm 1.8 ^b	3.2 \pm 2.5 ^b	2.7 \pm 1.0 ^b
Number of sharply bending riffle	2.7 \pm 2.0	4.8 \pm 3.2	3.3 \pm 1.7	3.2 \pm 1.7	3.3 \pm 1.8	4.4 \pm 2.2	4.2 \pm 2.3	4.2 \pm 2.6	3.9 \pm 3.3
Number of bar-head wando	4.1 \pm 2.0 ^{bc}	5.5 \pm 2.8 ^{ab}	7.1 \pm 2.7 ^a	4.9 \pm 2.2 ^{abc}	4.3 \pm 1.8 ^{bc}	4.5 \pm 1.8 ^{abc}	3.6 \pm 1.5 ^{bc}	3.9 \pm 2.3 ^{bc}	2.6 \pm 1.5 ^c
Number of bar-tail wando	6.8 \pm 3.9 ^{ab}	8.8 \pm 3.2 ^a	7.2 \pm 3.2 ^{ab}	7.2 \pm 3.8 ^{ab}	4.5 \pm 1.7 ^b	5.8 \pm 3.2 ^{ab}	4.3 \pm 2.0 ^b	7.7 \pm 4.3 ^{ab}	6.1 \pm 2.8 ^{ab}
Number of active pond	8.7 \pm 6.6 ^b	16.6 \pm 5.5 ^a	8.9 \pm 8.4 ^b	7.7 \pm 5.7 ^b	5.2 \pm 7.3 ^b	5.0 \pm 3.2 ^b	4.8 \pm 3.0 ^b	7.9 \pm 6.2 ^b	6.2 \pm 4.3 ^b
Number of terrace pond	6.5 \pm 5.4 ^b	7.5 \pm 7.4 ^b	8.4 \pm 6.9 ^b	7.3 \pm 6.6 ^b	5.7 \pm 4.2 ^b	5.4 \pm 3.0 ^b	7.2 \pm 5.0 ^b	8.7 \pm 3.9 ^b	13.2 \pm 8.9 ^a
Habitat richness	7.62 \pm 18.8	7.58 \pm 9.4	7.77 \pm 16.7	7.85 \pm 9.9	7.77 \pm 6.9	7.77 \pm 11.2	8.0 \pm 9.7	8.0 \pm 18.6	7.85 \pm 14.9
Habitat evenness	0.92 \pm 0.05 ^{ab}	0.88 \pm 0.08 ^b	0.93 \pm 0.03 ^{ab}	0.91 \pm 0.04 ^{ab}	0.92 \pm 0.06 ^{ab}	0.96 \pm 0.03 ^a	0.93 \pm 0.06 ^{ab}	0.92 \pm 0.03 ^{ab}	0.88 \pm 0.09 ^b
Habitat diversity	1.86 \pm 0.14 ^{ab}	1.78 \pm 0.15 ^b	1.91 \pm 0.07 ^{ab}	1.87 \pm 0.09 ^{ab}	1.88 \pm 0.15 ^{ab}	1.96 \pm 0.07 ^a	1.94 \pm 0.12 ^{ab}	1.92 \pm 0.05 ^{ab}	1.81 \pm 0.22 ^{ab}
Habitat soundness	0.28 \pm 0.16	0.31 \pm 0.14	0.34 \pm 0.13	0.26 \pm 0.09	0.17 \pm 0.06	0.28 \pm 0.14	0.26 \pm 0.12	0.33 \pm 0.19	0.24 \pm 0.19

Table 2.5. Historical changes in habitat structures and reach-scale geomorphological parameters (mean \pm standard error) in the Kizu River between 1948 and 2012. All the parameters were measured per each 2 km reach. Number of reaches measured: n=13 except for 1961 (n=12).

	1948	1961	1971	1979	1990	2002	2006	2010	2012
Reach-scale geomorphological parameters									
Wavelength (m)	1.80 \pm 0.9	2.61 \pm 0.7	1.87 \pm 0.7	1.71 \pm 0.4	1.68 \pm 0.6	1.75 \pm 0.5	2.07 \pm 0.6	2.02 \pm 0.7	1.88 \pm 0.7
Number of channels (CN)	2.12 \pm 0.84 ^a	2.07 \pm 0.35 ^a	1.95 \pm 0.40 ^{ab}	1.81 \pm 0.47 ^{ab}	1.66 \pm 0.37 ^{ab}	1.80 \pm 0.32 ^{ab}	1.44 \pm 0.24 ^b	1.41 \pm 0.21 ^b	1.52 \pm 0.23 ^b
Sinuosity	1.07 \pm 0.04	1.10 \pm 0.07	1.11 \pm 0.08	1.09 \pm 0.07	1.09 \pm 0.07	1.12 \pm 0.08	1.11 \pm 0.08	1.12 \pm 0.08	1.09 \pm 0.07
Channel width (m)	280.8 \pm 26.1 ^a	276.8 \pm 35.8 ^a	204.8 \pm 51.1 ^b	177.0 \pm 52.0 ^{bc}	154.8 \pm 36.6 ^{cd}	129.8 \pm 29.3 ^{cd}	128.9 \pm 37.0 ^{cd}	115.1 \pm 33.2 ^{cd}	144.4 \pm 39.8 ^{cd}
Floodplain vertical shape index (FVSI)		-0.45 \pm 0.10 ^c	-0.38 \pm 0.14 ^{bc}	-0.33 \pm 0.17 ^{abc}	-0.25 \pm 0.17 ^{abc}	-0.18 \pm 0.18 ^{ab}	-0.17 \pm 0.17 ^a	-0.16 \pm 0.16 ^a	-
Ratio of water-surface	0.43 \pm 0.14 ^a	0.31 \pm 0.05 ^b	0.31 \pm 0.61 ^{bc}	0.23 \pm 0.04 ^{cdc}	0.28 \pm 0.037 ^{bc}	0.20 \pm 0.29 ^{de}	0.19 \pm 0.38 ^{de}	0.16 \pm 0.34 ^e	0.24 \pm 0.05 ^{bcd}
Ratio of bare-land	0.50 \pm 0.16 ^c	0.63 \pm 0.58 ^c	0.34 \pm 0.11 ^b	0.28 \pm 0.12 ^{bc}	0.21 \pm 0.11 ^{bc}	0.22 \pm 0.09 ^{bc}	0.20 \pm 0.12 ^c	0.23 \pm 0.12 ^{bc}	0.21 \pm 0.09 ^{bc}
Ratio of bush-land	0.07 \pm 0.04 ^c	0.05 \pm 0.37 ^c	0.28 \pm 0.11 ^b	0.41 \pm 0.11 ^a	0.42 \pm 0.09 ^a	0.49 \pm 0.10 ^a	0.44 \pm 0.11 ^a	0.47 \pm 0.08 ^a	0.43 \pm 0.08 ^a
Ratio of wood-land	0.002 \pm 0.01 ^d	0.01 \pm 0.01 ^d	0.07 \pm 0.04 ^c	0.08 \pm 0.04 ^{bc}	0.1 \pm 0.04 ^{bc}	0.10 \pm 0.05 ^{bc}	0.17 \pm 0.06 ^a	0.15 \pm 0.72 ^{ab}	0.13 \pm 0.08 ^{abc}
Bed slope (mm ⁻¹)		0.00096	0.00082	0.00086	0.00085	0.00088	0.00092	0.00092	

2.3 RESULTS

2.3.1 Historical changes in habitat structures and RSCC

Historical changes in habitat structures and reach scale geomorphological parameters in the Kizu River during 1948-2012 are shown in Table 2.5. Abundance and area of total habitats consistently decreased, but abundance of habitats slightly increased in the 2010s. Gently bending riffle and active pond significantly increased in 1948 and 1961 respectively. Most habitats except for terrace ponds decreased during 1948-2012, and terrace pond significantly increased in 2012. Habitat evenness was higher in 2002 than in 2012, and habitat diversity was also higher in 1971 and 2002 than in 1961 and 2012. Habitat richness and soundness did not differ significantly.

The number of channels and channel width decreased consistently from 2.12 to 1.52 and from 280.0 to 144.4 respectively, but they slightly increased in 2012 (Table 5). Floodplain vertical shape index (FVSI) increased consistently, although the rate of increase decreased in the 2000s. On the other hand, sinuosity and bed slope did not change significantly within a range of 1.07 - 1.12 and 0.00082-0.00096, respectively. In landscape composition, the ratio of water-surface and bare-land decreased from 43 % to 24 % and from 50 % to 21 % respectively, whereas the ratio of vegetation (bush-land + wood-land) increased significantly from 7 % to 55 %.

Figure 2.4 illustrates geomorphological characteristics of the 8 channel types. Channel width tended to increase with channel types from Ssi to Bsi channel types (Fig. 2.4a). In contrast, FVSI showed lower values in Bsi channel types than in Ssi, SWst (slightly wandering straight channel) and SWsi channel types (Fig. 2.4b). The ratio of vegetation also showed similar trends to FVSI (Fig. 2.4d). Bed slope did not differ significantly in channel types (Fig. 2.4c). Thus, Bsi channel types were characterized by a wide channel width and a significantly concave vertical shape with a low vegetation area. In contrast, Ssi channel types were characterized by narrow channel width and approximately straight vertical shape with considerable vegetation expansion.

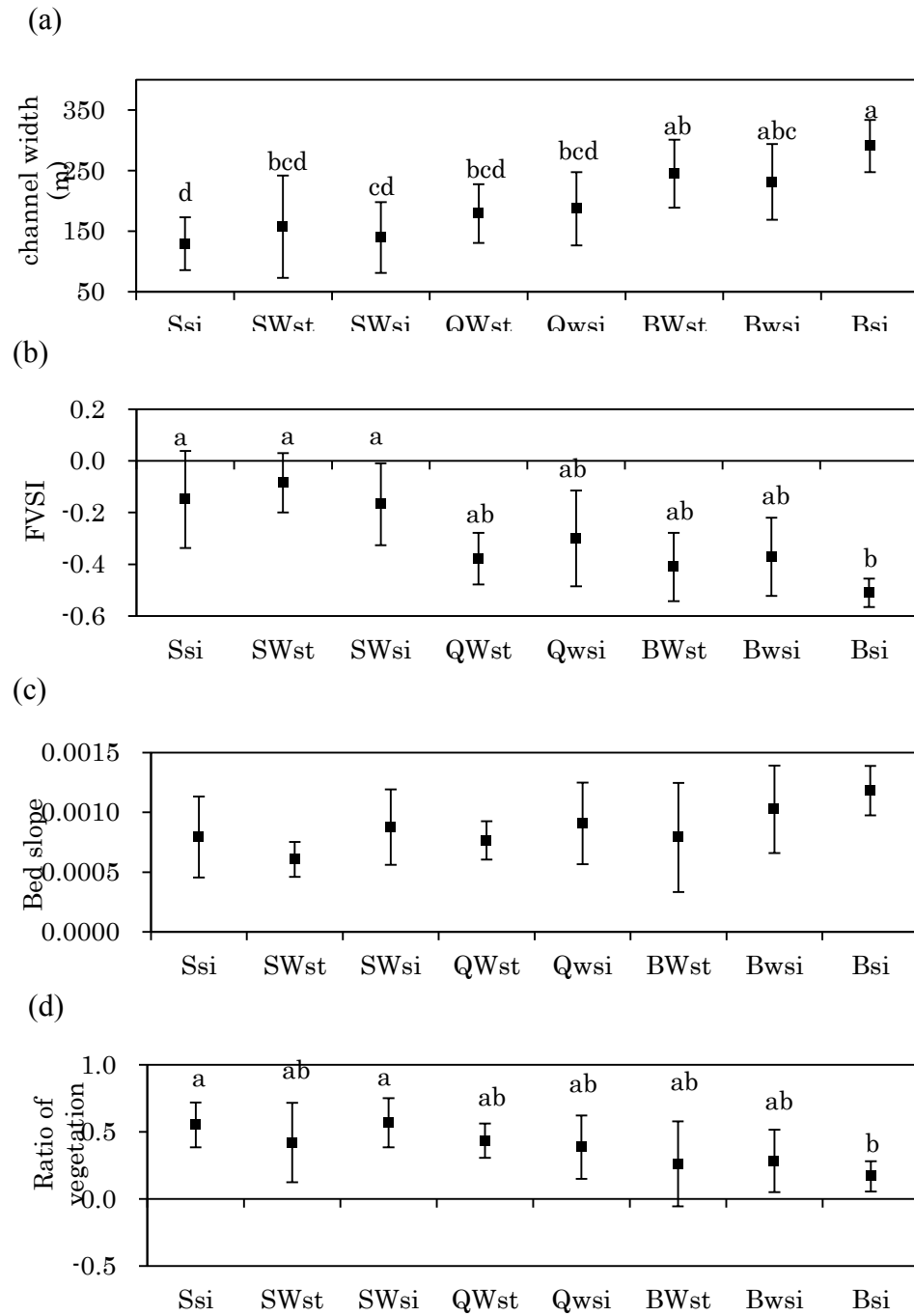


Fig. 2.4 Geomorphological characteristics of channel types; (a) channel width, (b) Floodplain vertical shape index (FVSI), (c) bed slope, and (d) ratio of vegetation area (wood +bush-land). n= Ssi (7), SWst (6), SWsi (34), QWst (11), Qwsi (36), BWst (4), Bwsi (14), Bsi (4)

Channel type composition of the Kizu River showed distinctive changes

historically (Fig. 2.5). Bsi and BWsi channel types disappeared after 1971 and 2002, respectively. Number of QWsi channel types significantly decreased in 2006 and 2010, and slightly increased in 2012. In contrast, the Ssi channel type appeared after 1971, and the number of SWsi channel types sharply increased in 2006 and 2010 with a reduction in variety of channel types.

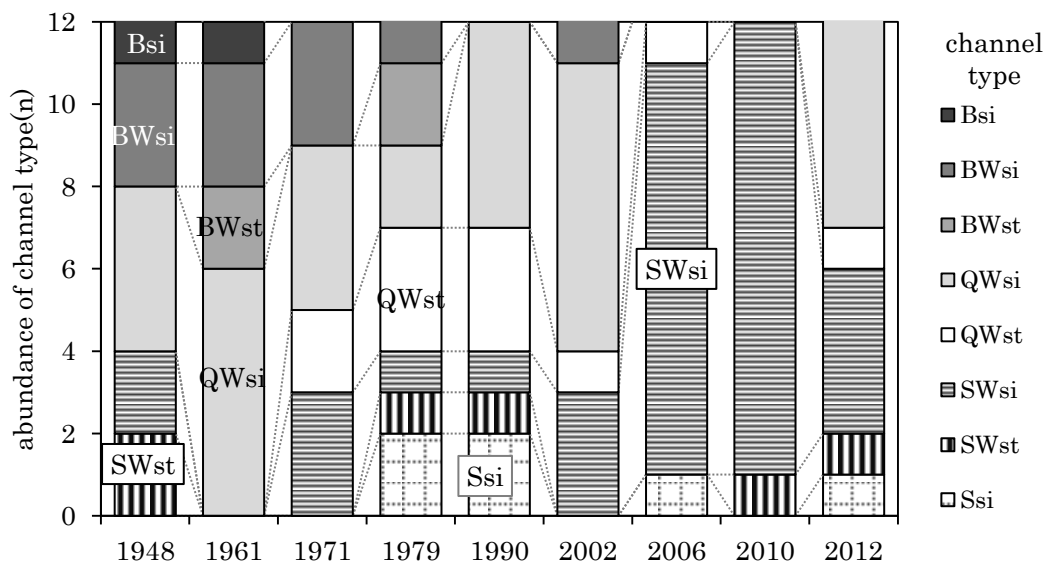


Fig. 2.5 Historical changes in the number of reaches showing each channel type in the Kizu River

2.3.2 Relations of habitat structures and RSCC

Total number of habitats for 8 habitat types were significantly different among channel types (Fig. 2.6), and the number of habitats for each habitat type was different among them (Fig. 2.7). The total number of habitats tended to increase with channel types from Ssi to Bsi channel types, thus, the total habitats were greater in Bsi than Ssi, SWst and QWst channel types. As for the number of each type of habitat, lotic habitats (secondary slow, gentle bending riffle, sharply bending riffle) except for main slow had maximum values in Bsi channel types (Fig 2.7a-7d). These habitats tended to increase gradually from Ssi to Bsi channel types. The number of all lotic habitats was more values in sinuous channels than straight channels in

slightly, quite and bifurcated wandering channels, although there was no significant difference: e.g. the abundance of secondary slow was greater in SWsi than in SWst. Abundance of lentic habitats showed maximum or minimum values in specific channel types. Bar head-wando represented the greatest number in BWsi channel types (Fig. 2.7e), and bar tail-wando was in Bsi channel types (Fig. 2.7f). Active pond tended to increase in QWsi and BWst, although the difference was not significant statistically (Fig. 2.7g). Abundance of terrace pond was greatest in SWst channel types and least in Bsi channel types (Fig. 2.7h).

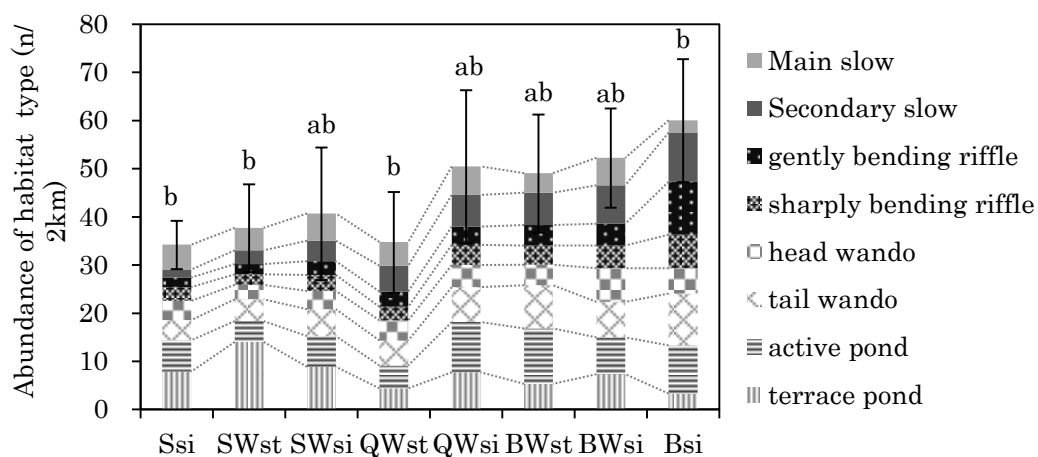


Fig. 2.6 Comparison of abundance of 9 habitat types among 8 channel types in the Kizu River based on all the data in 1948-2012

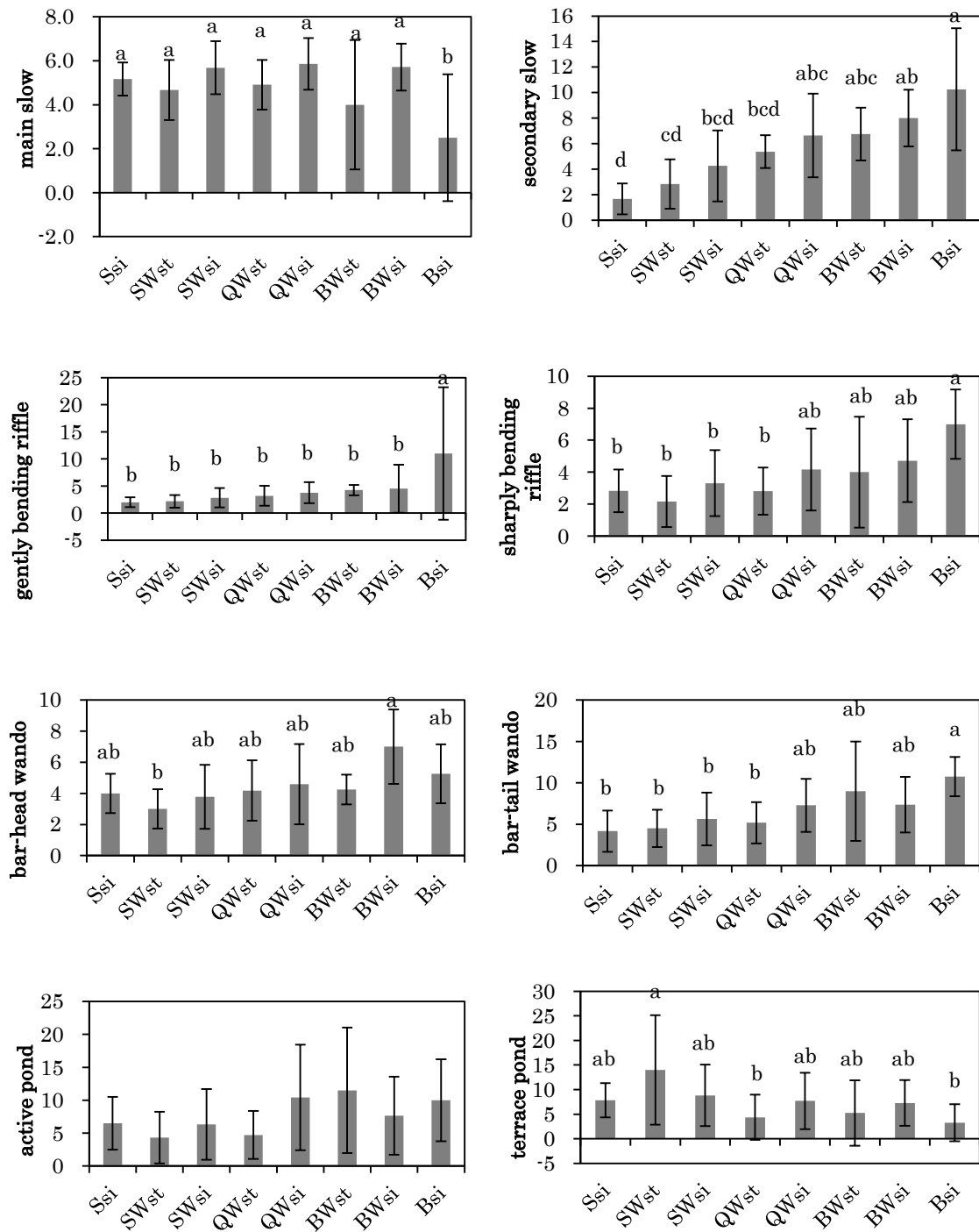


Fig. 2.7 Relations of abundance of each habitat (n/2km) to channel types (mean values and SD). n = Ssi (7), SWst (6), SWsi (34), QWst (11), QWsi (36), BWst (4), BWsi (14), Bsi (4)

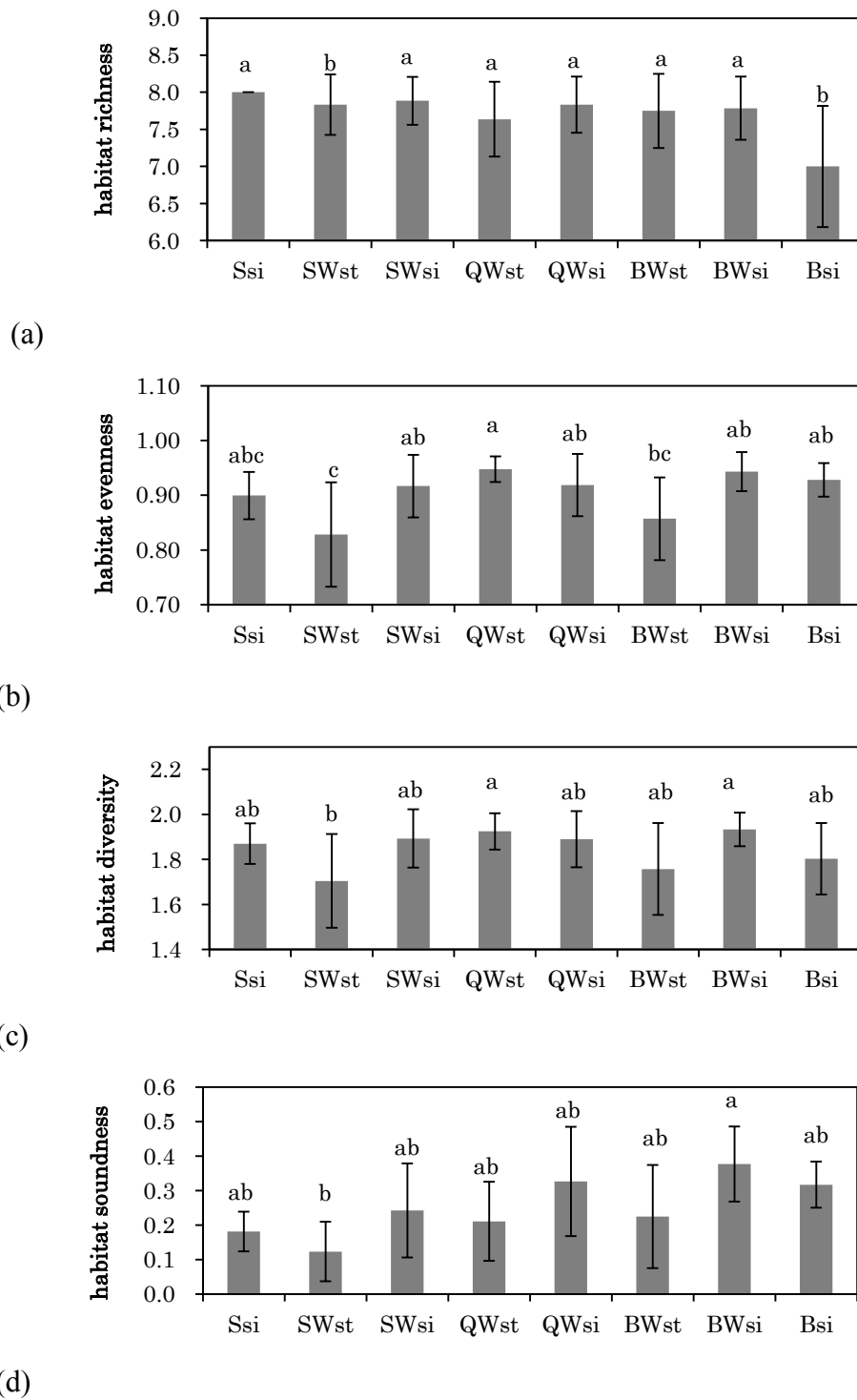


Fig.2.8 Relations of (a) habitat richness, (b) habitat evenness, (c) habitat diversity and (d) habitat soundness to channel types (mean values and SD). n = Ssi (7), SWst (6), SWsi (34), QWst (11), QWsi (36), BWst (4), BWsi (14), Bsi (4)

Variations in each habitat index (richness, evenness, diversity and soundness)

were analyzed in relation to 8 channel types (Fig. 2.8). Habitat richness showed lesser values in Bsi channel types than in the other channel types (Fig. 2.8a). Habitat evenness and diversity showed similar trends. Habitat evenness had more values in QWst channel types than in SWst and BWst channels (Fig. 2.8b). Habitat diversity showed more in QWst and BWsi channel types than SWst (Fig. 2.8c). Habitat soundness was the highest in BWsi channel types (Fig. 2.8d), and tended to have higher values in sinuous channel than straight, although the difference was not significant statistically.

2.3.3 Relations of RSCC and disturbance

Fig. 2.9 illustrates the relations of the number of channel types per year (Fig. 2.5) to the intensity of disturbance (annual sediment transport and maximum discharge) and frequency (number and durations of flood events per year) (Table 2.1). Yearly numbers of BWsi and Bsi channel types were positively related with annual sediment transport and Q_{max} (Fig. 2.9a, b). However, their abundance did not increase with the increase of annual sediment transport from 80,000 m^3/y to 110,000 m^3/y (Fig. 2.9a) and with the maximum discharge from 4,000 m^3/s to 6,000 m^3/s (Fig. 2.9b). In contrast, the number of SWsi channel types showed a negative relation to intensity of disturbance, even though this relation did not have significance. The abundance of QWst channel types showed maximum values between 4,000 and 7,000 m^3/y of annual sediment transport (Fig. 2.9a). Relations between the abundance of channel types and frequency of discharge did not have significance (Fig. 2.9c-f). Thus, abundance of Bsi, BWsi and QWst channel types showed significantly positive relations with intensity of disturbance, whereas significant relations with frequency of disturbance such as flooding events and durations of 3,000 m^3/s or 1,740 m^3/s were not shown.

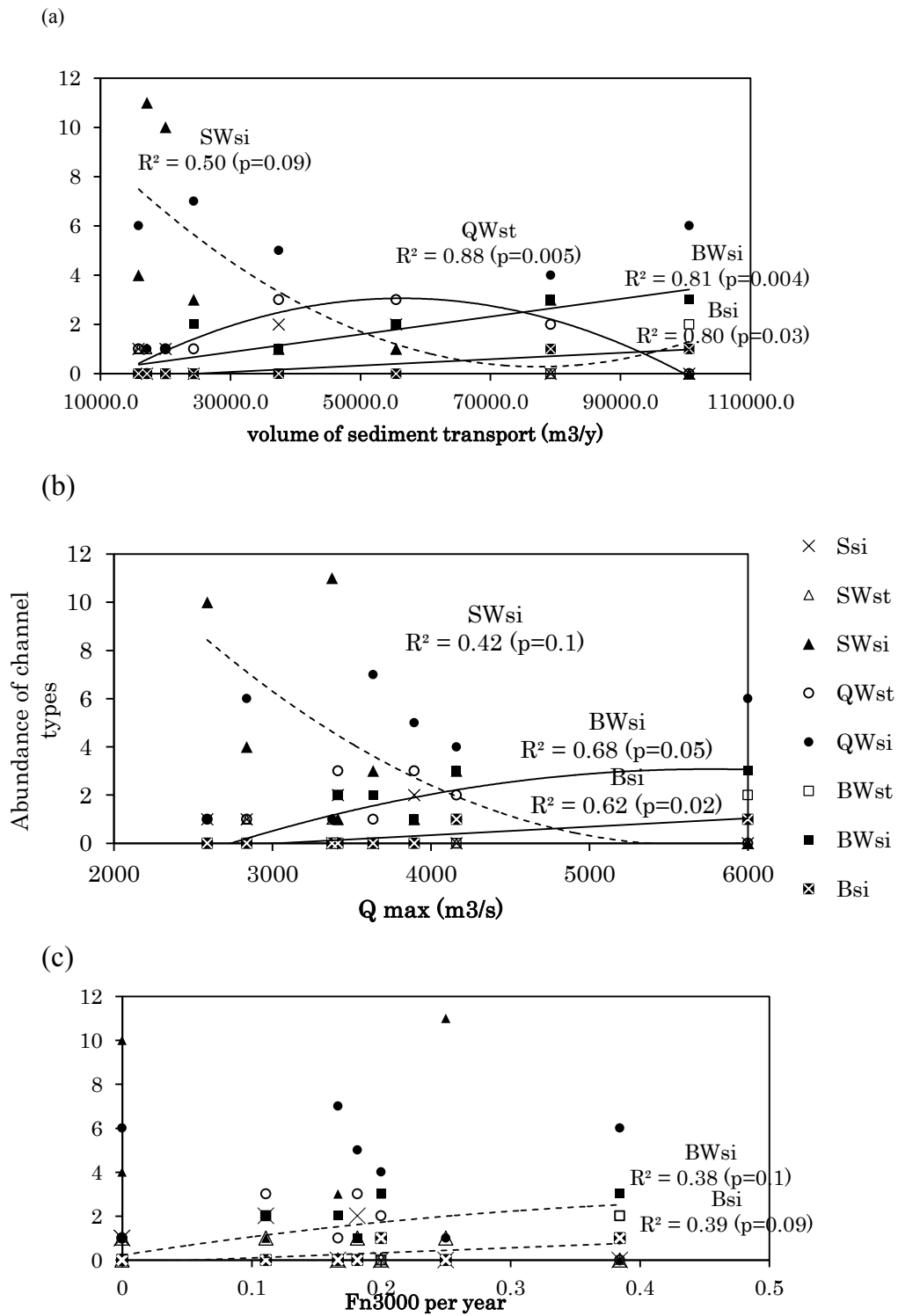
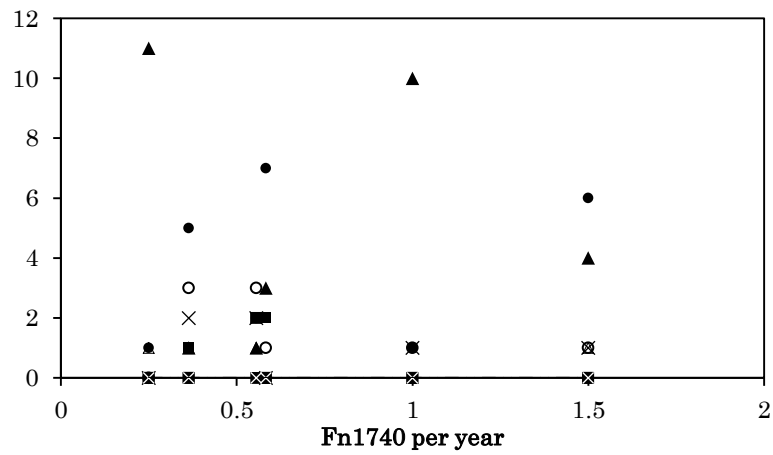
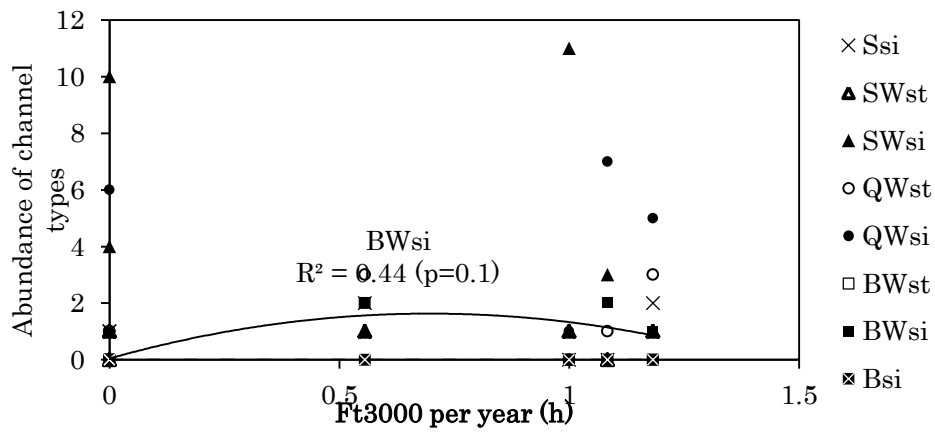


Fig. 2.9 Relation of abundance of channel types to disturbance regime; (a) annual sediment transport, (b) Qmax (maximum discharge), (c) Fn3000 (Number of flood events exceeding Q3000) per year

(d)



(e)



(f)

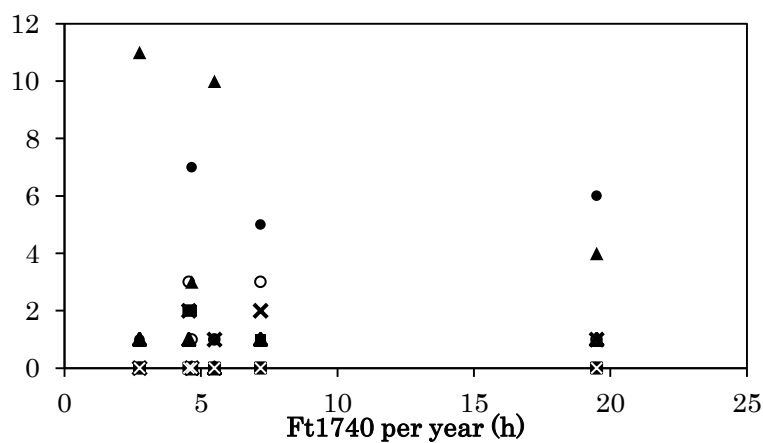


Fig. 2.9 Relation of abundance of channel types to disturbance regime. (d) F_{n1740} (Number of flood events exceeding Q_{1740}) per year, (e) F_{t3000} (flood durations exceeding Q_{3000}) per year, (f) F_{t1740} (flood durations exceeding Q_{1740}) per year.

2.4 DISCUSSION

2.4.1 Which types of channel types are suitable for habitat diversity?

Our results examined that braided channels were suitable for abundance of total habitats with high number of lotic habitats (Fig. 2.6; 2.7), and quite or bifurcated wandering channels were more stabilized than braided channels were suitable for diversity and abundance of both lotic and lentic habitats (Fig. 2.8). In terms of balance of lotic and lentic habitats than abundance of habitats, quite wandering straight channels or bifurcated wandering sinuous channels could be considered as most suitable conditions in the Kizu River. Because the Kizu River has been known as lotic habitats such as riffle and pool for Ayu fish (Kizu River Research Group, 2003) and invertebrates (Kobayashi and Takemon, 2013) as well as lentic habitats such as pool or wando for bitterlings and unionid mussels living in lentic habitats on its floodplain (Yodoqawa River Bureau, 2009), both lotic and lentic habitat should be considered obligatorily in the Kizu River.

However, generally, studies about relations between RSCC and habitat conditions for fish examined the advantages of braided channels. Sukhodolov et al. (2009) indicated that braided channels were shown to provide more favorable shelter and nursing conditions for fish larvae and juveniles by mitigation of high velocities during floods, by maintaining relatively shallow areas of flow, and by significant adjustments in the thermal regime. Payne and Lapointe (1997) examined a braid-like reach, dominated by a wide, dissected midstream bar, which offered three to five times more potential habitat for juveniles in terms of depth and velocity. Similarly, Beeachie et al. (2006) classified channel types in a forested mountain river into braided, island (vegetated) - braided, meandering and straight, and they concluded braided channels tended to have higher dynamics with floodplain turnover (low age) than other channel types.

Although this study also showed braided channels were suitable for abundant lotic habitats (Fig. 2.6), braided channels with many numbers of channels and bared island bars resulted in low number of main slow and terrace ponds (Fig. 2.7). Abundance of main slow tended to decrease in only braided channels, because braided channels

mostly consisted of shallow secondary slow. And terrace ponds tended to have more in slightly wandering straight channels than in braided channels, and thus, habitat richness decreased in braided channels (Fig. 2.8a). Relations between the abundance of ponds and floodplain vertical shape were studied by Takemon et al. (2013) in the Kizu River. They indicated that concave cross-section shapes had higher number of ponds (active ponds and terrace ponds) than approximate convex shapes or significantly concave shapes based on historical analysis of the Kizu River between 1961 and 2011. Their results could be more clearly explained using our results. The abundance of active ponds increased and terrace pond not was minimum in quite or bifurcated wandering channels having historically intermediate floodplain cross-section shapes, thus these channel types had the higher potential of abundance of ponds than single or slightly wandering channels and braided channels (Fig. 2.9). Similarly, the lower potential of riffles in braided channels before the 1970s of the Kizu River was discussed by Kobayashi and Takemon (2013) in terms of invertebrate communities. They classified riffle types and detected to that traverse or converge types of riffle (similar to sharply bending riffle) had higher biomass and taxonomic richness of invertebrates than diverge type of riffle (similar to gently bending riffle) by recent field survey. Then, the areas of each riffle type were measured using aerial photos and the potential of previous conditions was discussed. They predicted that invertebrates communities may be increase after the 1970s, and river conditions from the 1980s to the 2010s may have exhibited more biomass and richness than before. Although the areas of gently bending riffle increased in braided channels before the 1970s, they are unsuitable for high biomass.

The historical changes of the Kizu River indicated that braided or bifurcated wandering sinuous channels were characterized by wide channel width, concave floodplain shape and low vegetation area had disappeared, whereas single or slightly wandering sinuous channels were characterized by narrow channel width, relatively convex floodplain shape and high vegetation expansion increased during a 65-years period (Fig. 2.4). In other words, lateral stability of the Kizu River significantly and continuously increased after dam construction and sand excavation. Therefore, changes from present reaches to unstable conditions, but stabilized than braided

channels, should be required in the Kizu River to increase potential of habitat diversity and soundness of both lotic and lentic habitats.

2.4.2 Effects of reduction of disturbance on RSCC and habitat structure

Reduction of sediment supply and stabilized flow may cause variations in the geomorphic characteristics such as terrestrialisation of the vegetation with narrowing channel width (Table 2.5). Although the number of terrace pond increased according to increasing terrace area by vegetation expansion, quality of these ponds was threatened by a low inundation. Reduced connectivity in lentic habitats with the main channel caused habitat deteriorations such as a decrease in the diversity of bitterling and mussels, and the disappearance of representative protected bitterling '*Acheilognathus longipinnis*' (Kizu River Research Group, 2003).

If disturbances continuously decrease, channel in the Kizu River will be more stabilized, and thus, river health that could be adapted to natural disturbance (intermediate disturbance hypothesis: local species diversity is maximized when ecological disturbance is neither too rare nor too frequent; Connell, 1978) may be increasingly threatened. In order to restore river conditions, we should consider appropriate disturbance range. Although our analysis of relations between RSCC and disturbance regimes was insufficient to clearly explain their processes, intensity of disturbance such as volume of sediment transport and peak flooding was positively related to the presence of braided channels and bifurcated wandering sinuous channels (Fig. 2.9a; 2.9b). General, the role of disturbance intensity was widely known: for example, Brierley and Fryirs (2005) said that reduction of bed-load transport causes the increase of lateral stability, and Wishart et al. (2008) referred to the processes that frequent high magnitude flooding can rework both the channel bed and exposed bars and thus prevent vegetation colonization and lead to channel braiding. Volume of sediment transport more 40,000 m³/y or maximum discharge of about 4000 m³/s could help to increase the number of reaches having low lateral stability, however, the volume of sediment transport continuously decreased (Table 1), and peak discharge more than 4000 m³/s, did not occur after the 1990s (Fig. 2.1).

Although we did not detect significant relations between frequent flood discharge and channel types using historical data, RSCC and habitats were influenced by the intensity of flooding and sediment supply, and may be also influenced by durations of flooding. Slightly wandering sinuous channels in 2010 clearly changed to quite wandering sinuous channels in 2012 after long durations exceeding about Q1740 never been observed previously (Fig. 2.5). At the same time, the number of terrace pond significantly increased, thus habitat diversity significantly decreased (Table 2.5). Although flooding is crucial disturbance to change habitat structures in braided channels, e.g. even small water level fluctuations (flow pulses) can lead to major habitat changes such as habitat age (Van Der Nat et al., 2003), long durations of about intermediate intensity of flooding could increase specific habitat such as terrace pond in already stabilized floodplain in case of the Kizu River. Therefore, changing from current reaches to reaches having low lateral stability should be considered, and thus increasing intensity of disturbance required in the Kizu River.

2.4.3 Application of channel type classification to riverbed management

In order to accelerate disturbance in the downstream reaches of dam, comprehensive sediment management in basin scale has been developed worldwide including Japan, e.g. ‘sediment replenishment,’ ‘sediment bypassing tunnel,’ ‘flood mitigation dam’ without impoundment and dam removal (Sumi and Kantoush, 2010). Sediment replenishment works have been tested in the Kizu River basin such as in the Nunome River below Nunome Dam (since 2004), in the Uda River below the Murou Dam (2006), and Hinachi Dam (2008) and Shorenji Dam (2009) (Kantoush et al., 2010). For example, sediment for the replenishment works has been mechanically excavated at the check dam located at the upstream end of the reservoir, and moved to the downstream river below the dam by dump truck, then placed down on the bank far below the dam (Ock et al., 2013). Some researchers monitored or investigated effect of the sediment replenishment; In case of Uda River, changes of stockpiled sediment in downstream of Murou Dam monitored erosion or deposition of deposited sand shape and changes of grain size before

artificial flushing discharge, after artificial flushing and after natural flood based on thirteen points (Kantoush et al., 2010). Ock (2011) indicated that trapping efficiency of lentic plankton in the Nunome River that had tested sediment replenishment showed much higher than the Uji River. However, Ock et al, (2013) said that these applications still require a systematic development in the stages of planning and implementation, in particular, predicting flushing flows (magnitude, frequency and timing), determining quantity (amount added) and quality (grain size and source materials) of coarse sediment, and selecting effective implementation techniques for adding and transporting sediment in the fields. Our results can be applied to estimate reasonable sediment volume from ecological aspects, e.g. a volume of sediment transport of more 40,000 m³/y could be a target for in the Kizu River. And these implications by sediment replenishment or flushing could be reasonably predicted according to changes of RSCC such as increasing number of channels or channel width before survey of fauna communities.

2.5 CONCLUSION

This study aimed to understand relations between habitat structure and RSCC using historical data on river geomorphology and tried to link biology, geomorphology and hydraulics with multiple scales. The results of this study showed that braided or bifurcated wandering sinuous channels disappeared, whereas single or slightly wandering sinuous channels increased during a 65-year period in the Kizu River. As for relations between channel types and habitat structures, braided channel had the maximum number of total habitats with the highest number of bar-tail wando and lotic habitats except for main slow. And quite wandering straight channels had maximum habitat diversity, and bifurcated wandering sinuous channels had maximum habitat diversity and soundness. And thus, quite or bifurcated wandering channels more stabilized than braided channels were judged as suitable conditions in terms of the diversity and abundance of lentic and lotic habitats, although braided channels tended to have abundant habitats. Braided channels and wandering channels had positive relations with the intensity of disturbance such as annual sediment

transport and maximum discharge. Our results can be used to propose target RSCC for ecological river management, and to estimate reasonable discharge or sediment volume for habitat diversity in the Kizu River.

Chapter 3. Evaluation of RSCC based on bitterling-mussel abundance and lentic habitat structure

ABSTRACT

The Kizu River, a branch of the Yodo River in the middle of Japan, had experienced riverbed degradation and vegetation expansion in response to a peak cut in discharge and reduction in sediment dynamism after sand excavation and dam construction over the course of 60 years. This paper described relations among the abundance of fish and mussel communities, habitat structures and reach-scale channel configuration (RSCC) to link between microhabitat scales and reach scales. A total of 120 ponds on the lateral bars and terraces were monitored regarding fish and mussel communities and habitat conditions in 2007 and 2010. These ponds were classified into bar head-active pond (BH-AP), bar head-terrace pond (BH-TP), bar tail-active pond (BT-AP) and bar tail-terrace pond (BT-TP). Flooding frequency was used as a key parameter reflecting habitat conditions for bitterlings and mussels, and

floodplain vertical shape index (FVSI) was used as a characteristic of RSCC. The relations were analyzed using data in 2007 and 2010, and they were connected with long-term changes of FVSI to evaluate historical changes in potential habitat suitability for bitterlings and mussels. Results indicated that terrace ponds (BH-TP, BT-TP) having flooding frequency between 8 and 22 days/ year were the most suitable habitats for bitterlings and mussels. The number of suitable habitats increased on reaches with FVSI values between -0.35 and 0.05 . The suitable reaches having FVSI values between -0.35 and 0.05 tended to appear more from the 1980s to 2000s than before, and thus, the RSCC of the Kizu River after the 1980s seemed to have a higher potential for bitterlings and mussels.

3.1 INTRODUCTION

In the last decade, many rivers experienced riverbed degradation and vegetation expansion in response to peak discharge and flood frequency (Williams and Wolman, 1984; Takemon, 2010). In the case of the Kizu River, reduction of peak discharge and sediment supply may have influenced the narrowing channel width and decreasing number of channels with deposited sediment on bars (Table 2.5 in chapter. 2). These river channel alterations have led to the deterioration of lentic habitat conditions by the reduction of connectivity with the main channels. Many lentic ponds or wando providing habitat to bitterlings and unionid mussels were distributed on floodplains in the Kizu River. However, the diversity of bitterlings and mussels decreased, and representative protected bitterling *Acheilognathus longipinnis* had disappeared after sand excavation and dam construction (Kizu River Research Group, 2003). To improve river health, it is necessary to find out what habitat conditions are required for species diversity, especially for bitterlings and mussels.

Mussels could be used as an indicator of fish communities. Negishi et al. (2013) noted that the taxon richness of mussels was a good predictor of all fish community variables in drainage channels. Actually, mussels and fish had symbiotic relationships (Haag and Warren, 1998; Fig. 3.1). The reproduction of mussels requires gobby fish as hosts (Haag and Warren, 1998) and bitterlings use mussels for

spawning bed (Yoshihiro and Takashi, 2010). Thus, bitterlings and mussels are useful target species to evaluate habitat conditions for animal communities, not only mussels but also fish.

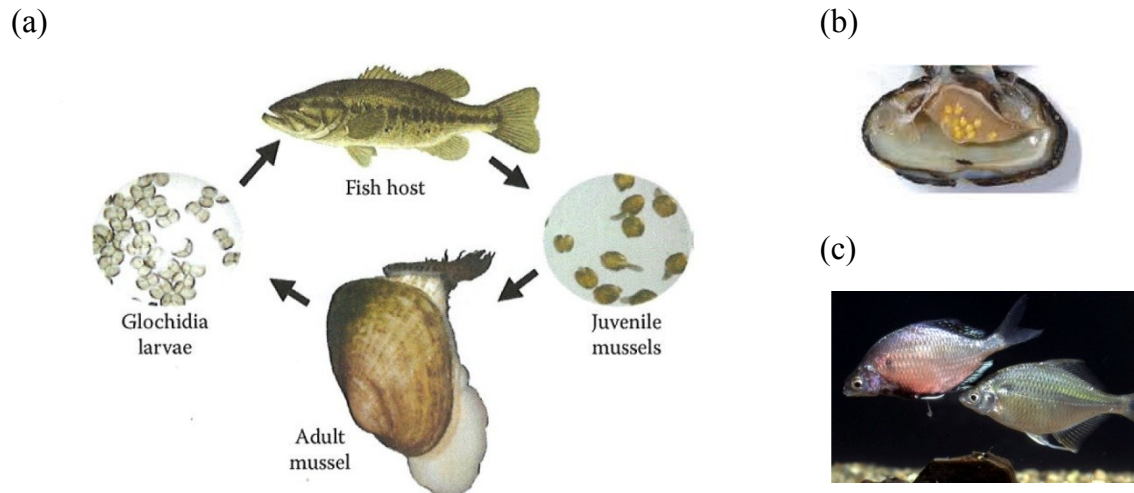


Fig. 3.1 Mussel life (a), egg of bitterling in mussel (b), bitterling (c)

Multiple spatial scales are a critical consideration for understanding ecological patterns (Tiegs et al., 2009). A hierarchical stream network is composed of scales of basin, segment, reach, pool/riffle and habitat (Frissell et al., 1986). Reach and large-scale watershed characteristics can affect community composition and environmental conditions (Poole and Downing, 2004). In spite of the potential importance of the large/basin scale, much of the study of mussel-habitat relationships has been performed on the scale of the local scale (Tiegs et al., 2009). Otherwise, relations between reach or basin scales and animal communities without habitat structure or conditions were difficult to understand. Processes and mechanisms of creation and maintenance of habitats responded to changes of disturbance.

To link between microhabitat scales and reach scales for animal communities, we described relations among the abundance of bitterling and mussel communities, lentic habitat structures and conditions (habitat scale) and floodplain vertical shape index (FVSI as parameters of RSCC) in the Kizu River. Values of FVSI could be used as representative parameters of RSCC because they can reflect changes of

channel type (Fig. 2.4 in chapter. 2). Furthermore, since FVSI was calculated by the relative height of bars using cross-section data (Table 2.2 in chapter. 2), it offers the most useful parameters for relations with lentic habitats on bars. The purpose of this paper is to show appropriate RSCC supporting habitats for bitterlings and mussels based on linkage among species, habitats and RSCC and to estimate historical changes in potential habitat suitability by changes in FVSI. Further, we suppose the suitable volume of sediment transport related to historical changes in potential habitat suitability to connect river management at the basin scale.

3.2 METHODS

3.2.1 *Study area*

The study area was established in the lower reaches (0~26 km) of the Kizu River, a tributary of the Yodo River in central Japan (Fig. 1.5). The Kizu River has been called a typical sandy river derived from weathered granite in the upper stream. The study area was composed of bareland (ca. 21%), bushland (ca. 42%), woodland on the floodplain (ca. 14%), and water surface (ca. 23%). The vegetation area on the floodplain increased about 8 times, and the bareland area decreased about 70% compared to 1948 (Choi et al., 2012).

3.2.2 *Abundance of species*

The data we used of the abundance of bitterlings and mussels were surveyed by the Yodoqawa River Bureau. The number of floodplain ponds detected in aerial photos in 2006 and 2010 was 190 and 178, respectively, and 47 and 73 floodplain ponds were surveyed in September 2007 and August 2010, respectively. Surveyed data of the abundance of bitterlings and mussels were divided by surveyed time (h) and number of attended people (n). In this study, abundance means total number of species.

3.2.3 Parameters of habitat conditions and habitat types

Lentic habitat types were classified into bar head-active pond (BH-AP), bar head-terrace pond (BH-TP), bar tail-active pond (BT-AP) and bar tail-terrace pond (BT-TP) using aerial photos in 2006 and 2010; active pond was defined as a pond that was located on active channels, and terrace pond was defined as a pond located on a terrace. A total of 9 parameters of habitat condition were selected: area, water depth, mud depth, mean grain size, dissolved oxygen (DO), chlorophyll, wood coverage (shaded shoreline ratio by wood), relative height and flooding frequency (Table 3.1). Relative height was calculated by the lowest height between the water level of the main channel and the level of a 5 m buffer around ponds using DEM data. Flooding frequency means inundation frequency in a pond per year. It was calculated by simulation using DEM data and water discharge of 10 years (0: none, 1: 1 time, 2: 8 times, 3: 16 times, 4: 22 times, 5: 45 times, 6: 71 times, 7: 185 times and 8: 365 times flooding per 1 year) (Table 3.1). All ponds detected on aerial photos (n= 368) had values of relative height and flooding frequency.

Table 3.1 Discharge per flooding frequency at Innooka observatory (16 km from conjunction)

1 (day)	8 (days)	16 (days)	22 (days)	45 (days)	71 (days)	185 (days)
909.1	249.5	149.0	118.3	72.9	52.9	26.2

3.2.4 Reach scale channel configuration

Reaches of the study area were divided into 2 km units according to the mean wavelength of alternative bars in the Kizu River. FVSI was used as a representative parameter of RSCC, because changes of FVSI significantly related with changes of channel planform, e.g., channel width, number of channels, ratio of vegetation, and of cross-section. FVSI was calculated by the difference of integral values of relative elevation of the riverbed to normal water level and those of uniformly distributed elevation within a 2 km unit based on cross-sectional profiles at intervals of 200 m. FVSI shows a degree of convex or concave shape in the altitude distribution of the

floodplain. The positive value is reflected in the convex vertical shape, and the negative value is reflected in the concave vertical shape. Values of FSVI were calculated based on data of 7 years in 1961, 1971, 1979, 1990, 2002, 2006 and 2010. Only results of 2 years (2006 and 2010) were connected with habitat structures and abundance of species, and values in other years were used for the evaluation of historical changes in potential habitat suitability.

3.2.5 Statistical analyses

To find a key parameters among habitat conditions for the abundance of bitterlings and mussels, multiple and single regression analyses were used. The best model was selected based on Akaike's Information Criterion. In order to know relations between the selected key parameter and bitterlings and mussels, the abundance of bitterlings and mussels was transferred to a suitable index (SI). The maximum value of abundance was transformed to 1, and the minimum value was 0. An α value of 0.05 was used to indicate statistical significance for all tests. All analyses were conducted using SPSS version 19 (SPSS 19.0, SPSS Inc.).

3.3 RESULTS

3.3.1 Abundance of bitterlings and mussels in habitat conditions and types

Bitterlings were observed in 63 ponds and mussels were observed in 47 ponds among 120 ponds in total. Values of habitat conditions per pond type were shown in Table 3.2, and the abundances of bitterlings and mussels were shown in Table 3.3. Terrace ponds (BH-TP, BT-TP) had deeper mud depth, more chlorophyll and wood coverage, higher relative height and lower flooding frequency than active ponds (BH-AP, BT-AP). Especially, pond type BT-TP had the maximum values in mud depth, chlorophyll and wood coverage (Table 3.2).

Pond type BT-TP had the maximum abundance of bitterlings among all pond types. The abundance of mussels showed more values in terrace ponds (BH-TP and BT-TP) than active ponds (BH-AP, BT-TP) (Table 3.3).

Table 3.2 Habitat conditions per habitat type

	Area (m ²)	Water depth (m)	Mud depth (m)	Mean grain size (mm)	DO (mg/ l)	Chlor ophyll (µg/l)	Wood cover age (%)	Relati ve height (m)	Floodin g frequenc y
All ponds	507± 882	46.7± 23.6	8.1± 10.0	3.6± 4.8	9.8± 4.7	90.1± 145.1	11.1± 19.7	1.4± 1.2	3.5± 2.1
BH-AP	390± 611	48.7± 22.4	5.4± 6.5	3.7± 4.1	10.2± 3.5	40.6± 63.1	4.3± 10.9	0.9± 0.5	4.5± 1.8
BH-TP	411± 494	42.7± 25.5	7.9± 8.9	4.3± 5.5	10.3± 4.8	54.4± 81.9	10.6± 21.4	2.0± 1.5	2.7± 1.6
BT-AP	678± 879	51.9± 28.8	5.4± 8.8	3.4± 3.2	9.2± 4.9	28.5± 35.8	8.7± 14.7	0.7± 0.3	5.4± 1.9
BT-TP	575± 1218	45.2± 20.2	11.6± 12.5	3.0± 5.5	9.6± 5.4	185± 203.7	18.1± 24.2	1.8± 1.3	2.2± 1.6

Table 3.3 Abundance of bitterlings and mussels across all 120 ponds and each pond type (mean ± standard error.). n= BH-AP (31), BH-TP (28), BT-AP (21), BT-TP (40)

	Abundance of bitterlings	Abundance of mussels
All ponds	7.0 ± 20.2	15.7 ± 43.2
BH-AP	3.1 ± 6.7	4.2 ± 17.8
BH-TP	3.6 ± 5.6	27.6 ± 57.4
BT-AP	2.6 ± 5.0	4.9 ± 12.6
BT-TP	14.7 ± 32.9	21.9 ± 52.6

3.3.2 Relations of habitat conditions to bitterlings and mussels

The best models of habitat conditions for the abundance of bitterlings and mussels were selected based on all pond types. Only selected habitat conditions in the best models were shown in Table 3.4. The abundance of bitterlings was best explained by a model consisting of mud depth, chlorophyll, relative height and flooding frequency, and the abundance of mussels was best explained by a model

consisting of area, wood coverage, relative height and flooding frequency. Mud depth tended to have negative relations with the abundance of bitterlings (Fig. 3.2a), and chlorophyll had positive relations. Habitat size and wood coverage were positively related to the abundance of mussels (Fig. 2b). Relative height and flooding frequency were important variables in explaining the abundance of bitterlings and mussels because they were selected in both models.

Two parameters, relative height and flooding frequency, had significant correlations with each other (Fig. 3.3a) and had negative correlations with the abundance of bitterlings and mussels. Flooding frequency also tended to have relations with mud depth and wood coverage even though they had low coefficients (Fig. 3.3b, 3.3c). Although flooding frequency did not have relations with habitat size, we determined flooding frequency as a key parameter reflecting habitat conditions for the abundance of bitterlings and mussels.

Table 3.4 Results of multiple regression analysis that examined the best models of habitat conditions for the abundance of bitterlings and mussels

	Area (m ²)	Water depth (m)	Mud depth (m)	Mean grain size (mm)	DO (mg/l)	Chloro phyll (µg/l)	Wood covera ge (%)	Relati ve height (m)	Floodi ng freque ncy
Abun. of bitterling s			-0.6 (0.24)			0.08 (0.26)		-7.8 (0.26)	-3.0 (0.24)
Abun. of mussels	0.01 (0.16)						0.41 (0.16)	-15.8 (0.18)	-8.7 (0.18)

Habitat parameters were included as independent variables in the best models on the basis of Akaike's Information Criterion. (Regression coefficients presented for each best model, parentheses indicate level of contribution.) Abun. is abundance.

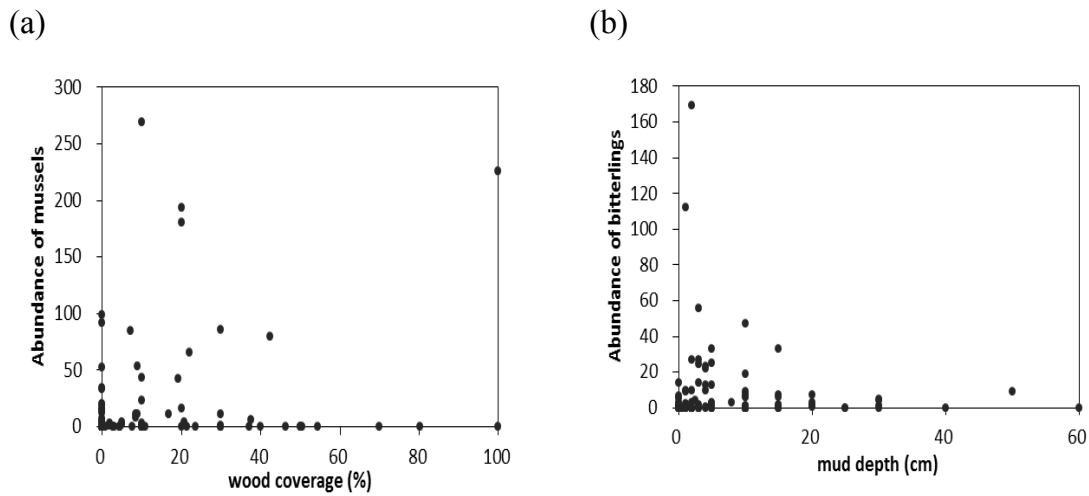


Fig. 3.2 Relations of (a) mud depth to abundance of bitterlings and (b) wood coverage to abundance of mussels

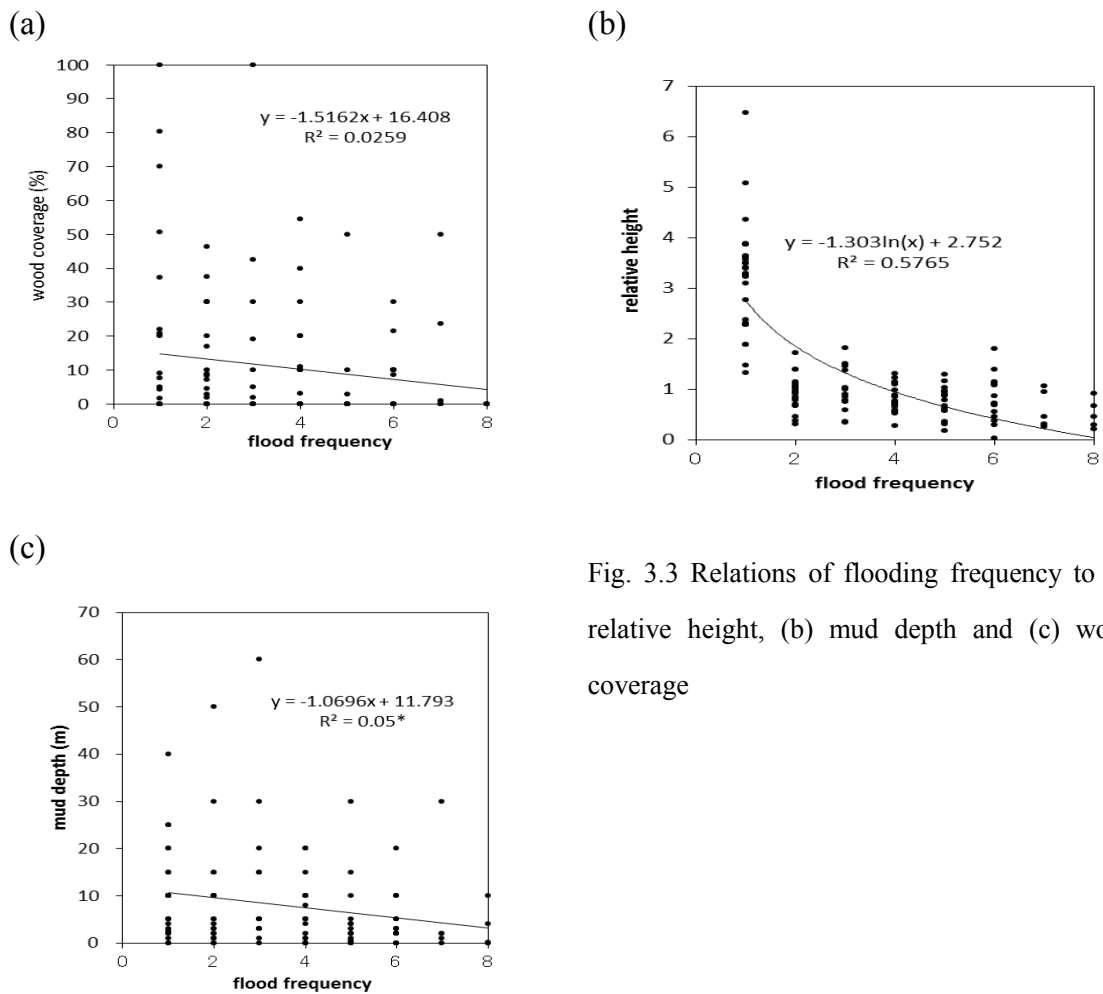
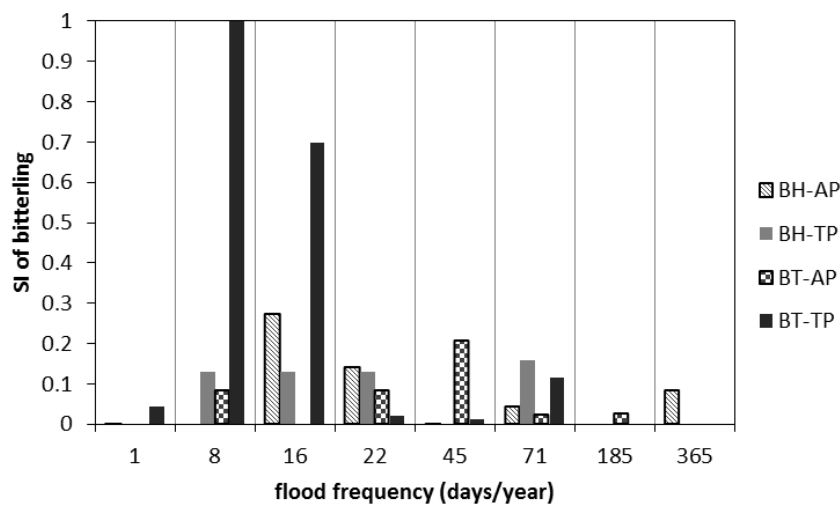


Fig. 3.3 Relations of flooding frequency to (a) relative height, (b) mud depth and (c) wood coverage

The parameter of flooding frequency was related with the suitability index (SI) of bitterlings and mussels (Fig 3.4). The SI of bitterlings tended to have high values in BT-TP between 8 and 16 days/year of flooding frequency (Fig. 3.4a). The SI of mussels tended to have high values in BT-TP and BH-TP between 8 and 22 days/year of flooding frequency (Fig. 3.4b).

(a)



(b)

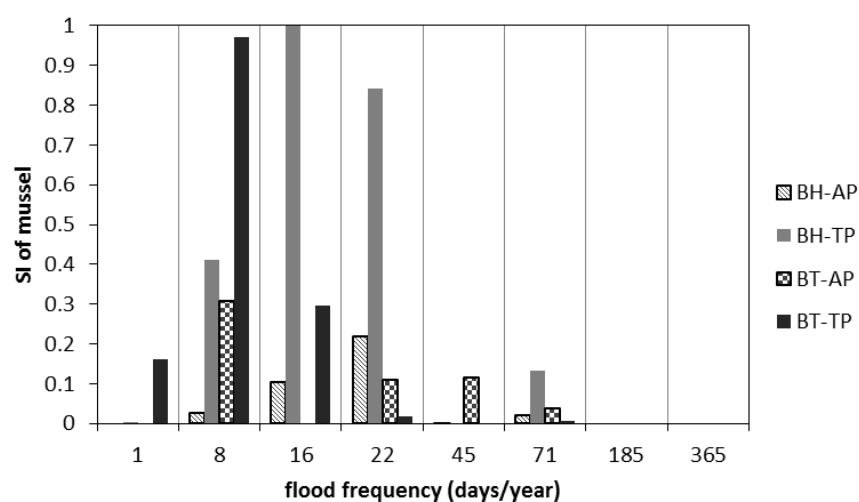


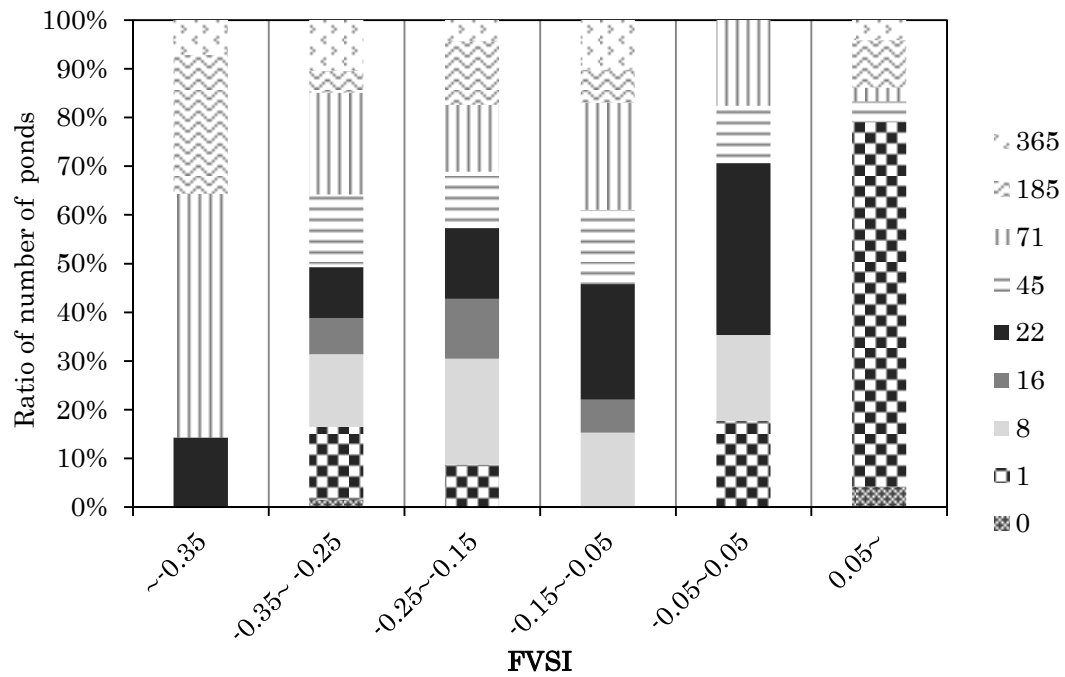
Fig. 3.4 Relations of flooding frequency to (a) SI of bitterlings and (b) SI of mussels

3.3.3 Relations of representative habitat conditions to RSCC

FVSI as a parameter of RSCC was categorized into 6 groups (Fig. 3.5). The number of ponds having different flooding frequencies was counted by categorized values of FVSI, and then was changed to ratio (Fig. 3.5a). All ponds, not only surveyed ponds but also those detected in aerial photos, ($n = 386$) were used in this relation. The ratio of the number of ponds having a flooding frequency between 8 - 22 days/year showed higher values in FVSI between -0.35 and 0.05 . Reaches with FVSI values of less than -0.35 had a high number of ponds with frequent flooding frequency, such as 45 or 71 days/year. On the other hand, the number of ponds having a flooding frequency of 1 time/year significantly increased in areas with FVSI values exceeding 0.05 . That is, frequently flooded ponds tended to exist on a reach with significant concave floodplain shape, whereas ponds having a low flooding frequency tended to show in convex floodplain shape.

The number of pond types was also counted by values of FVSI (Fig. 3.5b). Pond types of BH-TP and BT-TP increased with values of FVSI and a total number of 2 terrace pond types showed maximum values of FVSI exceeding 0.05 . In contrast, a number of active ponds (BH-AP, BT-AP) had maximum values of FVSI less than -0.35 . Terrace ponds tended to increase with the increase of values of FVSI, whereas active ponds tended to decrease in the same situation. Although the number of terrace ponds having suitable flooding frequencies for bitterlings and mussels increased with FVSI values exceeding 0.05 , they could be called suitable habitats; because these terrace ponds tended to have less flooding frequency (0 or 1 days/year). Thus, reaches having FSVI values between -0.35 and 0.05 tended to have a large number of ponds with suitable flooding frequencies for bitterlings and mussels.

(a)



(b)

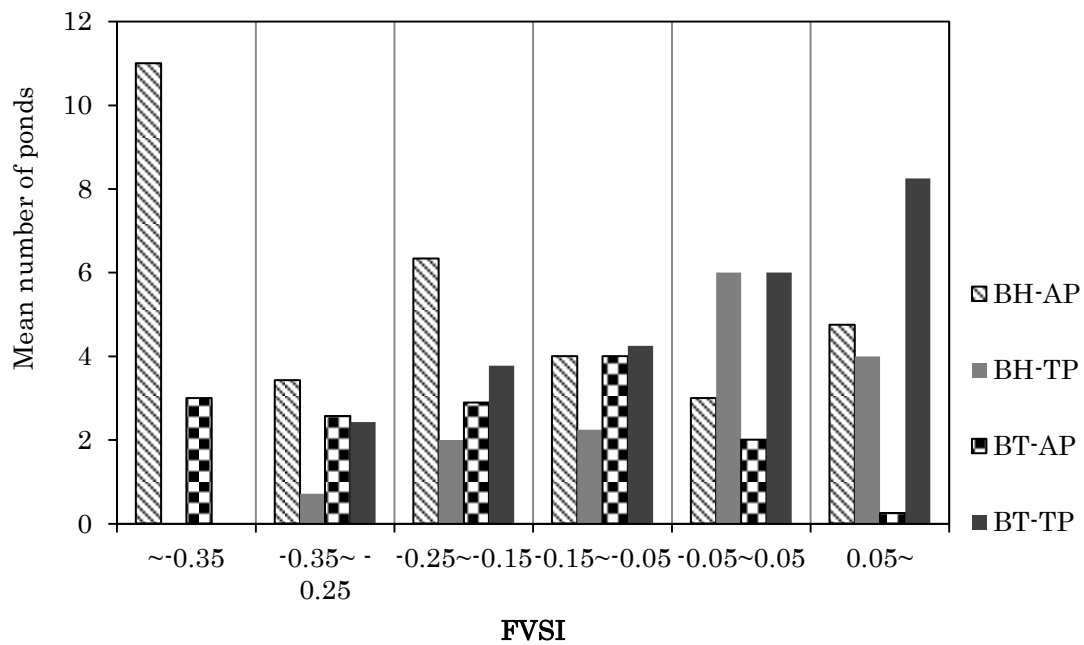


Fig. 3.5 Relations of floodplain vertical shape index (FVSI) to (a) ratio of number of ponds with different flood frequencies and (b) number of pond types.

3.3.4 Historical changes of FVSI

Historical values of FVSI were plotted in Fig. 3.6. Mean FVSI values significantly increased from -0.44 in 1961 to -0.17 in 2010. Reaches having FVSI values between -0.35 and 0.05 tended to appear more after the 1980s than before. Reaches before the 1980s showed significantly more concave shapes than in the present.

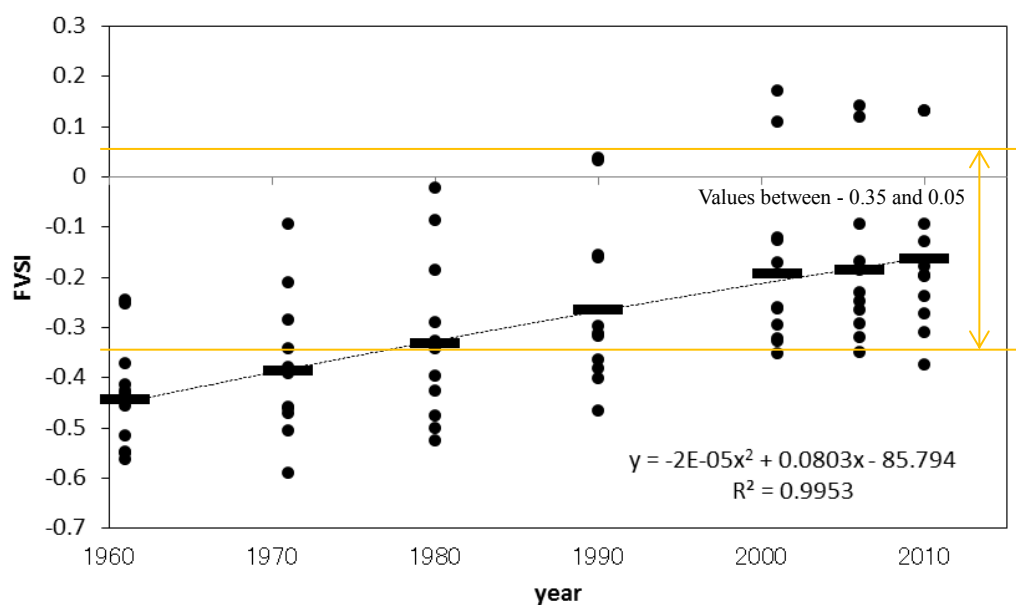


Fig. 3.6 Historical changes of FVSI; rectangles indicate mean values each year

3.4 DISCUSSION

3.4.1 Suitable habitat conditions for the abundance of bitterlings and mussels

We supposed flooding frequency is one of the important attributes in explaining the abundance of bitterlings and mussels, because it influences various environmental factors directly or indirectly. In this study, terrace ponds having a low flooding frequency (8 - 22 days/year) tended to have higher mud depth, vegetation

coverage and chlorophyll than active ponds (Table 3.2). Negishi et al. (2012) compared flooding frequency with other potentially important environmental variables (ORP, organic matter and chlorophyll) in backwater for mussel distribution. They explained that low inundation frequency tended to result in high levels of chlorophyll. And thus, flooding frequency was considered as an important criterion of the stability of habitat conditions on lotic habitats such as wetlands or ponds. This study showed that bitterlings and mussels may increase in relatively stable habitat conditions compared to unstable conditions, such as active pond, in which frequent flooding occurs and the habitat is easily changed or may disappear. Because mussels live partially or completely buried in the sediment of rivers (Morales et al., 2006), they require an appropriate depth of sediment in stable conditions. In the case of aquatic invertebrates, ephemeral and temporary lakes tended to have fewer taxa than semipermanent channel or terminal lake habitats (Sheldon et al., 2002).

However, although mussels increased in stable habitat conditions having a low flooding frequency, a significantly low flooding frequency (0 - 1 times/year) caused a low abundance of bitterlings and mussels (Fig. 3.4) because a low flooding frequency may deepen mud depth due to continuous deposition of mud, and then mussels in deep mud will be difficult to breath due to the reduction of DO. Negishi et al. (2012) detected survival rates of mussels were low and growth rates nearly 0 in infrequently inundated water bodies (backwater, wetland) by field-eating experiments, and in these water bodies, hypoxia ($DO < 2 \text{ mgL}^{-1}$) was frequently observed. However, these researchers noted that the abundance of mussels significantly an increased with increased frequency of inundation associated with flood pulses in the Kiso River. Probably this difference between the Kiso River and the Kizu River resulted in geomorphic conditions located in ponds. Since the Kiso River had a mostly vegetated narrow floodplain, habitat conditions almost never changed, and thus, water bodies on the floodplain depend on inundation. On the other hand, the Kizu River had a wide floodplain consisting of bare and vegetated land, and thus, frequent floods influenced geomorphic channel changes, such as the expansion of bare land, disappearance of habitats or changing habitat type. Thus, in the case of the Kizu River, intermediate mud depth with intermediate flooding

frequency, not frequent or absent flooding, was required to increase the potential of bitterlings and mussels.

3.4.2 Volume of sediment required for suitable habitats for bitterlings and mussels

According to linkage between habitat and RSCC, habitat having a suitable flooding frequency of 8 - 22 days/year increased in reaches with FVSI values between -0.35 and 0.05 (Fig. 3.5). Significantly concave reaches with FVSI values lower than -0.35 can be easily inundated, even with a small flood, and thus, ponds located on these reaches mainly were active ponds with frequent flooding. Although these active ponds had a low abundance of bitterlings and mussels, other fish might have been increased due to frequent connectivity with the main channel. The number of these reaches decreased and disappeared over 45 years in the Kizu River. According to chapter 2, braided channel types, which were characterized by a wide channel width and low vegetation area with a significantly concave vertical shape, decreased and disappeared. In contrast, slightly wandering channel types, which were characterized by narrow channel width and considerable vegetation expansion with approximately convex vertical shape increased (Fig. 2.4 in chapter. 2). Choi M. et al. (2013) examined the Kizu River experienced channel narrowing and a decreasing number of channels with significant increase in FVSI values by reduction of peak discharge and sediment supply in the past 50 years.

We detected present reach conditions, which mostly consisted of slightly wandering channels (Fig. 2.5 in chapter. 2), tended to be more suitable for bitterlings and mussels than before. Although the diversity of bitterlings and mussels decreased and representative protected bitterling *Acheilognathus longipinni* had disappeared (Kizu River Research Group, 2003) due to these channel changes, the present habitat conditions for the abundance of bitterlings and mussels were formed to be more suitable than before. This method for ecological evaluation of RSS based on habitat and species could apply to riverbed management on the basin scale. In the case of the Kizu River basin, sediment replenishment was tested in the Nunome River below Nunome Dam (since 2004), in the Uda River below the Murou Dam (2006),

and Hinachi Dam (2008) and Shorenji Dam (2009) (Kantoush et al., 2010). Ock et al., (2013) said that these applications require a systematic development in the stages of planning and implementation, in particular, predicting flushing flows (magnitude, frequency and timing), and determining quantity (amount added) and quality (grain size and source materials) of coarse sediment. We could estimate the quantity of suitable sediment supply for bitterlings and mussels based on the sediment discharge estimated in the suitable period. The Kizu River experienced consistent reduction of sediment transport after the dam construction and sand excavation between 1958 and 1963 (Ashida et al., 2008). According to relations between the estimated sediment discharge and suitable period (1980s - 2000s), the volume of sediment transport from the 1980s to 2000s (at around 20,000 - 50,000 m³/yr) could be required for maintain the suitable habitat for bitterlings and mussels (Fig. 3.7).

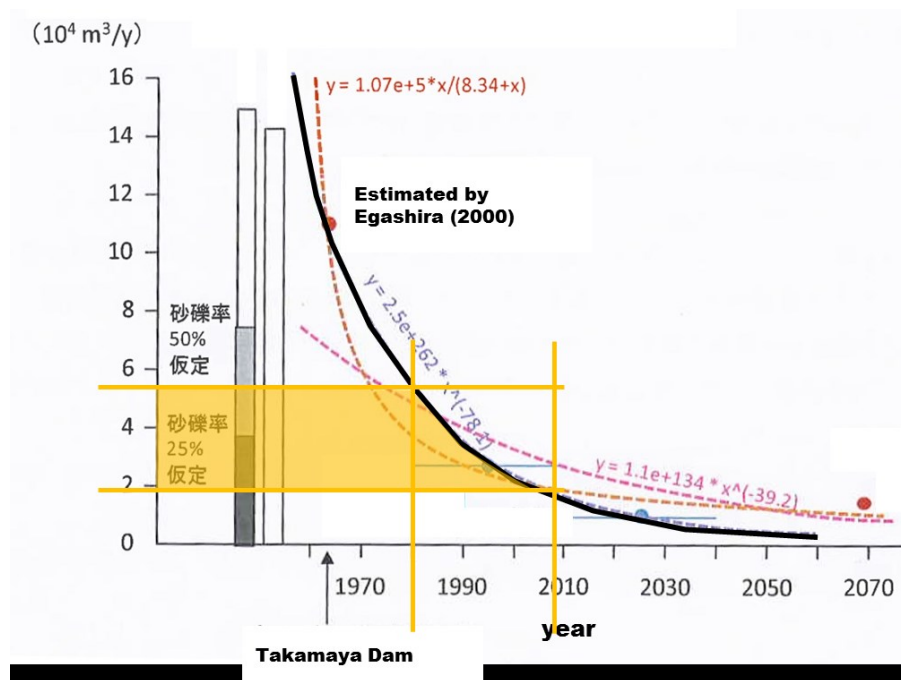


Fig. 3.7 Sediment transport required for bitterling and mussel

3.5 CONCLUSION

This paper described relations among the abundance of fish and mussels, habitat structure and RSCC in order to identify the suitable RSCC for the organisms. A total of 120 ponds on the lateral bars and terraces were monitored regarding fish and mussel communities and habitat conditions in 2007 and 2010. Flooding frequency was used as a key parameter reflecting habitat conditions for bitterlings and mussels, and FVSI was adopted as a RSCC parameter. Results indicated that terrace ponds having a flooding frequency between 8 and 22 days/ year were the most suitable habitats for bitterlings and mussels. The number of suitable habitats increased on reaches with FVSI values between -0.35 and 0.05 . The suitable reaches having FVSI values between -0.35 and 0.05 tended appear more from the 1980s to 2000s than before, and thus, the RSCC of the Kizu River after the 1980s seemed to have a higher potential for bitterlings and mussels. That is, the current reach condition, mostly consisting of slightly wandering channels, tended to have more suitability for bitterlings and mussels than before. According to relations between the estimated sediment discharge and suitable period (1980s - 2000s), the volume of sediment transport from the 1980s to 2000s (at around 20,000 - 50,000 m³/yr) could be required for bitterlings and mussels in riverbed management within the basin scale.

Appendix

Detected species of bitterling (Order: Cypriniformes, Family: Cyprinidae)

	Species	2007	2009
カネヒラ	<i>Acheilognathus rhombeus</i>	0	0
シロヒレタビラ	<i>Acheilognathus tabira tabira</i>	0	0
イチモンジタナゴ	<i>Acheilognathus cyanostigma</i>	0	0
タイリクバラタナゴ	<i>Rhodeus ocellatus ocellatus</i>	0	0
ヤリタナゴ	<i>Tanakia lanceolata</i>		0

Detected species of mussel (Order: Unionoida, Family: Unionidae)

	Species	2007	2009
マルドブガイ	<i>Anodonta calipygos Kobelt</i>	0	
ドブガイ	<i>Anodonta woodiana</i>	0	0
トンガリササノハガイ	<i>Lanceolaria grayana cuspidata</i>	0	0
ササノハガイ	<i>Lanceolaria oxyrhyncha</i> (Martens)	0	
イシガイ	<i>Unio douglasiae nipponensis</i>	0	0

Chapter 4. Historical influence of past environmental conditions on the present biodiversity in lentic habitat

ABSTRACT

The Kizu River ecosystem is characterized by lentic habitats such as pools or wando on the floodplain, providing habitats to *Acheilognathus* bitterlings and freshwater unionid mussels. In the last decade, however, these habitats have been degraded by the decrease of peak discharge and flooding frequency and excessive vegetation expansion on the floodplain. In order to restore the suitable habitat structure for the Kizu River ecosystem, it is necessary to find out relations of habitat conditions required for bitterlings, mussels and fish. For understanding the intrinsic reasons for their presence or absence in lentic habitats, such as active and terrace ponds, it is inevitably important to analyze historical effects of habitat conditions on species diversity. Thus, this study examined the historical influence of past environmental conditions on the present biodiversity in lentic habitats. Results showed that species richness of bitterlings was best explained by a model consisting

of location, age, transparency, mean grain size and dissolved oxygen (DO) 1 year ago. Species richness of mussels was best explained by a model consisting of flooding frequency and depth of mud 2 years ago. In contrast, species richness of resident fish and alien fish were significantly correlated with habitat conditions of the current year. Species richness of resident fish was best explained by low relative height, age, area and vegetation coverage, and that of alien fish was explained by a model consisting of low relative height, area, vegetation coverage and DO.

4.1 INTRODUCTION

The Kizu River has been known for bitterlings and unionid mussels living in lentic habitats, such as pools or wando, on its floodplain (Kizu River Research Group, 2003). In the last decade, however, these habitats have been degraded by the decrease of peak discharge and sediment supply along with excessive vegetation expansion on the floodplain (Ashida et al., 2008). According to the deterioration of habitat conditions, the diversity of bitterlings and mussels decreased, and representative protected bitterling *Acheilognathus longipinnis* had disappeared in the Kizu River (Kizu River Research Group, 2003). To restore the habitat structure of species diversity of bitterlings and mussels, it is necessary to find out relations of habitat conditions required for species diversity. Thus, most studies examined relations between mussels and habitat conditions such as water depth, bottom roughness, canopy (Strayer and Ralley, 1993), sediment softness, velocity and sediment type (Yoshihiro and Takashi, 2010), sediment type (Holland -Bartels, 1990), current velocity, sediment size, water depth (Johnson and Brown, 2000) or shear stress (Gangloff and Feminella, 2007). However, in order to understand the intrinsic reasons for their presence or absence in lentic habitats, such as active and terrace ponds, it is inevitably important to analyze the effects of habitat conditions not only at present but also in the past. Geomorphic habitat structure and conditions were influenced by deposition and scour in reaches by historical changes of disturbance, and thus historical effects are also very important for species. Most studies about historical effects on present species diversity focused on historical

changes of disturbances such as discharge or temperature (Inoue et al., 2014) or major floods (Hastie et al., 2001). These studies could detect the dynamic or frequency of disturbances that promoted species richness. However, it is difficult to know how habitat conditions changed by these disturbances and how changed habitat conditions influenced on current species diversity hierarchically. Thus, we tried to detect relations between current species diversity and past habitat conditions as well as current habitat conditions based on historical changes of discharge.

We focused on bitterlings and mussels as animal communities. Mussels could be used as an indicator of fish communities. Negishi et al. (2013) noted that taxon richness of mussels was a good predictor of all fish community variables in drainage channels. Reproduction of mussels requires goby fish as hosts (Haag and Warren, 1998), and bitterlings use mussels for spawning bed (Yoshihiro and Takashi, 2010). In addition, we used resident fish and alien fish, because exotic species and degraded water quality influenced declines of fish (Lydeard et al., 2004). Thus, we considered bitterlings and mussels as well as resident fish and predator alien fish.

The survival of mussels depends on the interaction of several biotic and abiotic factors operating at different spatial and temporal scales (Morales et al., 2006; Haag and Warren, 1998). Because successful reproduction requires the availability of an appropriate host fish at the appropriate time, mussels had the possibility of an existing time lag between past habitat conditions and current diversity. However, there have been a few works about these relations.

This paper aims to clarify the amount of time lag between habitat changes having a significant influence on species diversity of fish, bitterlings and mussels. In addition, we attempted to figure out habitat parameters that have a dominant role on species diversity.

4.2 METHOD

4.2.1 Study sites

The study area was established in the lower reaches (0~32 km) of the Kizu River, a tributary of the Yodo River in central Japan (Fig.1). The mean of river slope in the

study area was 1/1,180 and the mean diameter of bed material was 2 mm ~3 mm (Kizu River Research Group, 2009). The peak discharge of the river is caused by seasonal typhoons in summer and autumn. The largest flood event occurred in 1959 and reached almost 6,000 m³/s, whereas the intensity of peak discharge decreased by about 3,000 m³/s after the dam construction (Fig. 2.1a in chapter. 2). The annual mean discharge was about 25 m³/s and high discharge was about 43 m³/s. The annual mean bed-load transported to the lower reach was estimated to be about 183,000 m³/y in the 1960's, but about 23,000 m³/y in the 2000s (Ashida et al., 2008). The study area was composed of bareland (ca. 21%), bushland (ca. 42%), woodland on the floodplain (ca. 14 %) and water surface (ca. 23%). The vegetation area on the floodplain increased about 8 times, and bareland area decreased about 70% compared to 1948 (Choi et al., 2012).

4.2.2 Species richness

We used species and habitat condition data from the Yodoqawa River Bureau. Data of habitat conditions in 2007, 2009, 2010 and 2011 were used (Fig. 4.1), and species diversity in a total of 47 active ponds and terrace ponds in 2011 was used. Used ponds were selected by ponds having past conditions recorded in 2007, 2009 and 2010. Fish and mussel data were classified into bitterlings, mussels, resident fish and predatory alien fish (e.g. bass, blue gill, snake head). The species richness, which was defined as the total number of species, was used as species diversity.

4.2.3 Parameters of habitat conditions

The following parameters measured by the field surveys were used for the analyses: habitat size, area of water surface, water depth, area of water depth lower than 30 cm, transparency of water, water quality (PH, DO, COD, SS, EC, ORP), chlorophyll, vegetation coverage, ratio of floating plants, grain size (mean, D60, D50, D30), depth of mud, porosity and ignition loss, relative height (low, mean, high), flooding frequency, age and location. Relative height is height between the water level of the main channel and the level of a 5 m buffer around the pool. Flooding frequency was calculated by simulation using DEM data and water

discharge of 10 years (0: no flooding, 1: 1, 2: 8 times, 3: 16 times, 4: 22 times, 5: normally flooding per 1 year). The age of the ponds was defined by the existent period of habitat using aerial photo from 2001 to 2012, and the location was assigned a section number (0: lower site ~ 32: upper site). A total of 27 habitat condition parameters were considered as explanatory variables.

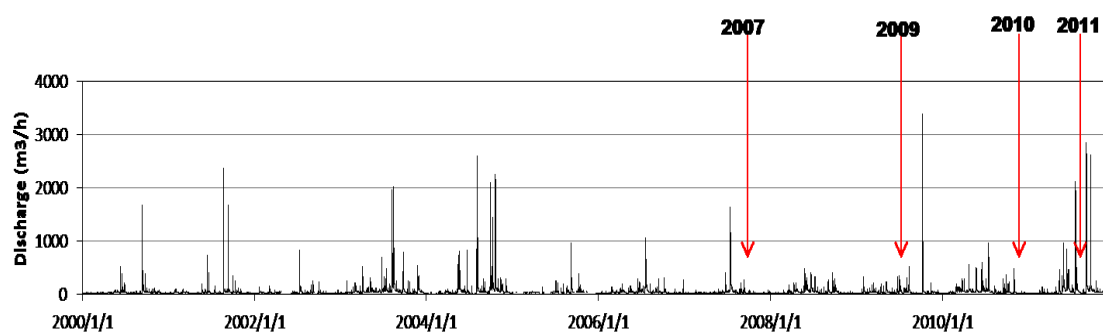


Fig. 4.1 Analyzed data of 4 years with annual discharge.

4.2.4 Statistical analyses

To select representative explanatory variables among many habitat conditions, we used correlation analysis and principal component analysis (PCA) for picking out data of habitat conditions related to species richness.

Relations of fish and mussel richness to habitat conditions were analyzed using a generalized linear model (GLM) with a Poisson error assumption and a long link function. Values of area and depth as explanatory data were log transformed, because they did not show normal distribution. The best model was selected based on Akaike's Information Criterion (AIC; Akaike, 1974), and chi-squared (χ^2) was used to compare the effect of past and recent conditions on fish and bivalve diversity. All analyses were conducted using SPSS version 19 (SPSS 19.0, SPSS Inc.).

4.3 RESULTS

4.3.1 Annual changes of habitat conditions

The final explanatory variables that were selected included low relative height, flooding frequency, age, location, habitat size, water quality (PH, DO), transparency, vegetation coverage, mean grain size, and depth of mud.

Some explanatory variables were compared to annual changes for each year (Fig. 4.2). Depth of mud significantly increased in 2009 and decreased in 2010 and 2011. DO increased in 2010 and 2011, whereas the ratio of vegetation coverage decreased from 2007 to 2010. Similarly to with depth of mud, the ratio of floating vegetation also increased in 2009.

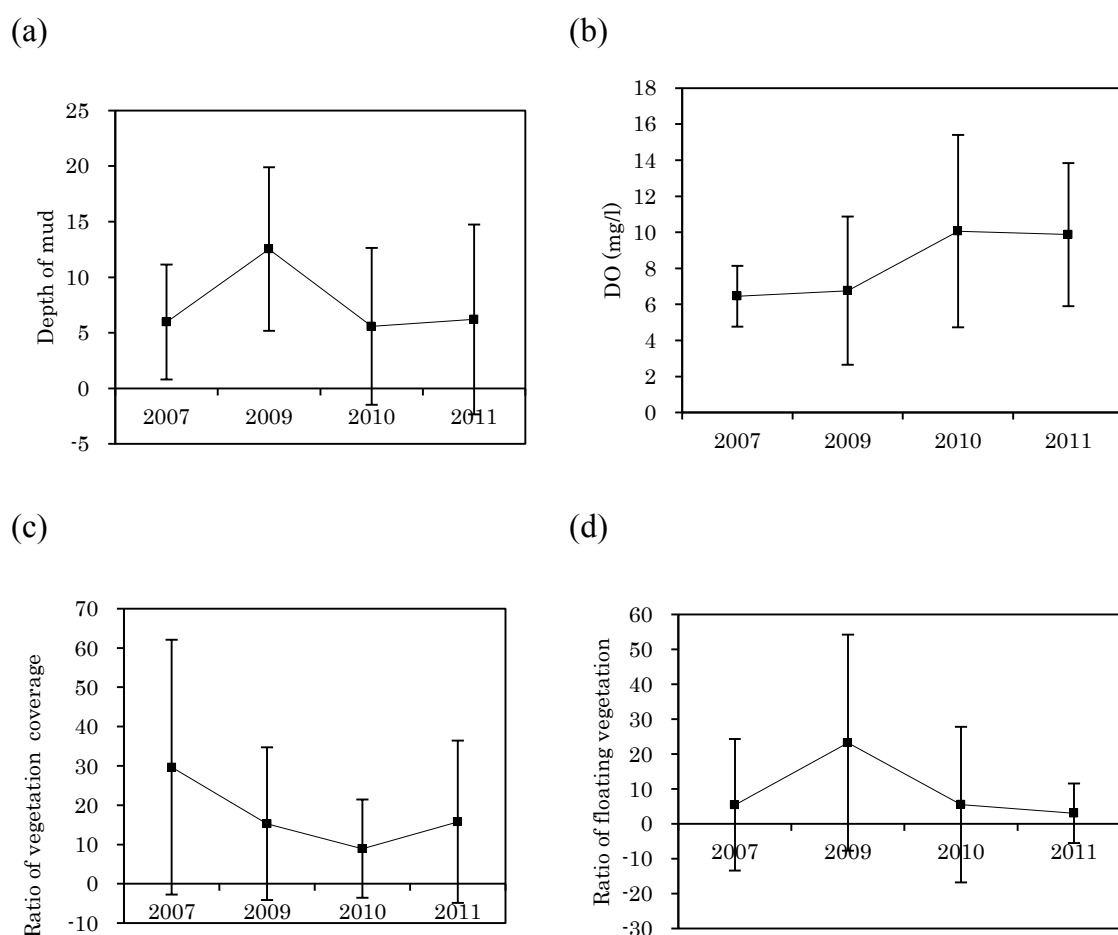


Fig. 4.2 Annual changes of habitat conditions (a) depth of mud, (b) DO, (c) ratio of vegetation coverage, (d) covered ratio by floating plants on water surface.

4.3.2 Relations between species richness and habitat conditions

Table 4.1 showed relations between current species richness and current and past habitat conditions. Species richness of bitterlings was best explained by a model consisting of location, age, transparency, mean grain size and DO 1 year ago ($\chi^2 = 3.83$, $P = 0.05$). Species richness of mussels was best explained by a model consisting of flooding frequency and depth of mud 2 years ago ($\chi^2 = 12.18$, $P < 0.001$). Species richness of resident fish and alien fish were significantly related to habitat conditions of the current year. Species richness of resident fish was best explained by low relative height, age, area and vegetation coverage ($\chi^2 = 18.34$, $P < 0.001$) and species richness of alien fish was explained by a model consisting of low relative height, area, vegetation coverage and DO ($\chi^2 = 20.42$, $P < 0.001$).

Table 4.1 Results of generalized linear model that tested the relations of species richness in 2011 and habitat conditions in 2007, 2009, 2010 and 2011. n is number of used parameters

Species richness	Model		n	Year	Wald χ^2	p-value
	Statistic data	Field survey data				
Bitterling	Location + age	Transparency + mean grain size + DO	5	2011	1.81	.177
				2010	3.83	.050
				2009	1.84	.174
				2007	3.15	.076
Mussel	Flooding frequency	Depth of mud	2	2011	0.56	.454
				2010	1.99	.157
				2009	12.18	.000
				2007	5.90	.015
Resident fish	Low relative height + age	Area + vegetation coverage	4	2011	18.34	.000
				2010	2.14	.143
				2009	1.13	.287
				2007	0.75	.386
Alien fish	Low relative height	Area + vegetation coverage + DO	4	2011	20.42	.000
				2010	0.28	.594
				2009	0.59	.441
				2007	0.55	.456

Table 4.2 Results of correlation analysis that tested relations between species richness and habitat conditions that were used in the model.

Species richness	Low relative height	Age	Location	Flooding frequency	Area	Vegetation coverage	DO	Transparency	Mean grain size	Depth of mud
Bitterling		.220	.331				-.203	-.151	-.007	
Mussel				-.454**						-.524**
Resident fish	-.394**	-.287			.324 *	-.350*				
Alien fish	-.288				.547***	-.341*	.438**			

Relations between bitterling richness in 2011 and habitat conditions in 2010, relations between mussel richness in 2011 and habitat conditions in 2009, and relations between fish richness in 2011 and habitat conditions in 2011 (r values: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$).

Table 4.2 indicated that relations between current species richness and past habitat conditions consisted of a selected model. Species richness of bitterlings had no significant correlations separately. Although it did not show correlation between bitterling diversity in 2011 and each habitat condition in 2010, species richness of bitterlings increased with high habitat age in Fig. 4.2. Species richness of mussels negatively related with flooding frequency ($R = -0.454$, $P < 0.01$) and depth of mud ($R = -0.524$, $P < 0.01$; Fig. 4.3). Species richness of resident fish had a negative correlation with low relative height ($R = -0.394$, $P < 0.5$) and vegetation coverage ($R = -0.35$, $P < 0.5$). Species richness of alien fish showed a negative correlation with vegetation coverage ($R = -0.341$, $P < 0.5$) and a positive correlation with habitat size ($R = .547$, $P < 0.5$) and DO ($R = 0.438$, $P < 0.5$) (Table 4.2).

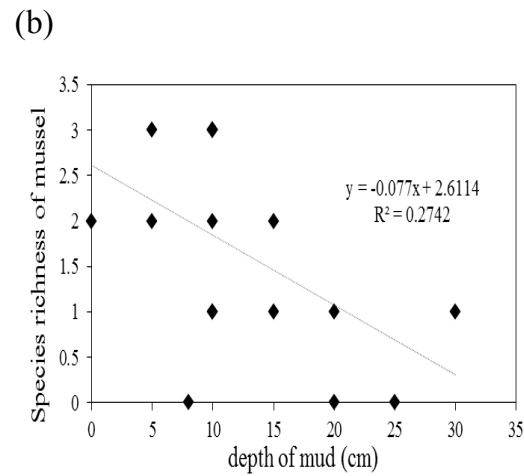
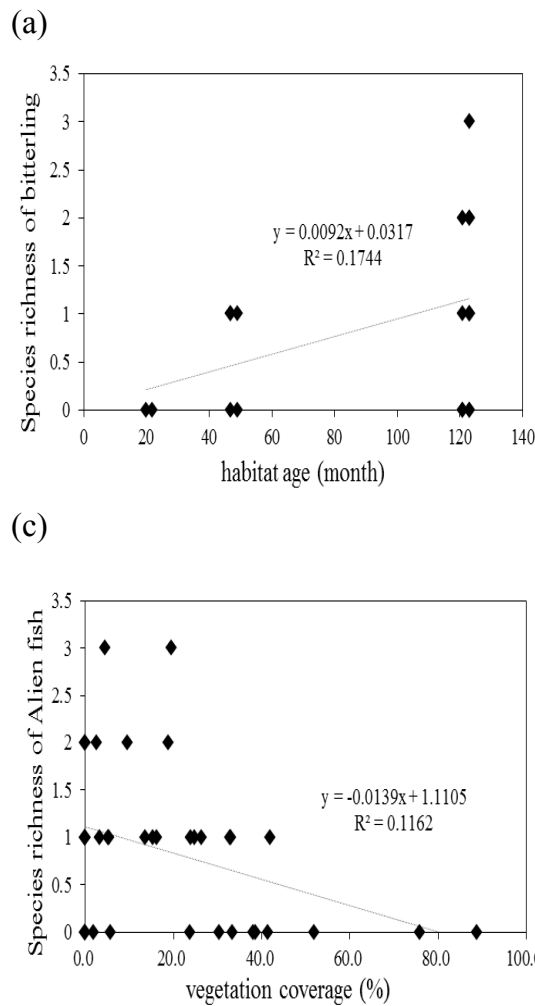


Fig. 4.3 Relations between (a) habitat age and species richness of bitterlings, (b) depth of mud and species richness of mussels and (c) vegetation coverage and species richness of alien fish

4.4 DISCUSSION

Our study showed that current species richness of resident fish and alien fish were significantly related to habitat conditions of the current year (Table 4.1). However, species richness of bitterlings and mussels showed higher relations with past habitat conditions than with current. The species richness of mussels was best explained by a model consisting of flooding frequency and depth of mud 2 years ago. Because mussels take about 5 years from reproduction to adulthood (McMahon and Bogan, 2001, Fig 4.4), the mussel cycle may require time for growth. According to Fig. 4.4, juvenile mussels emerge from gobby fish and drop back to the substrate for the cycle to begin. Since most mussels live their whole life in the same pond, habitat conditions when juvenile mussel emerge from gobby fish, especially mud depth

related with flooding frequency, seem to be important. According to chapter 3, we also detected that bitterlings and mussels were related with flooding frequency and mud depth. According to the Yodogawa River Bureau (2010), the ratio of juvenile mussels increased in 2009 (2 years ago) compared to 2007 and 2010. Since peak flood occurred with less than 500 m³/h during 2007 and 2009 (Fig. 4.1), habitat conditions tended to be stabilized, such as through increasing mud depth or floating plants (Fig. 4.2). In other words, stabilized habitat conditions in 2009 may have positively influenced increasing and maintaining juvenile mussels, and mussels that grew up may have been detected by the survey in 2011. However, as discussed in chapter 3, intermediate mud depth with intermediate flooding frequency, not frequent or absent flooding, is required to increase the potential of bitterlings and mussels because low flooding frequency may deepen mud depth due to continuous deposition of mud, and then mussels in deep mud will find it difficult to breathe due to the reduction of DO. This implies that a stable period without big floods is required for mussel abundance and richness. At the same time, intermediate disturbance is required for maintaining suitable mud depth. In order to maintain a healthy and sustainable habitat for fish and mussels, a wide range of habitat conditions should be considered.

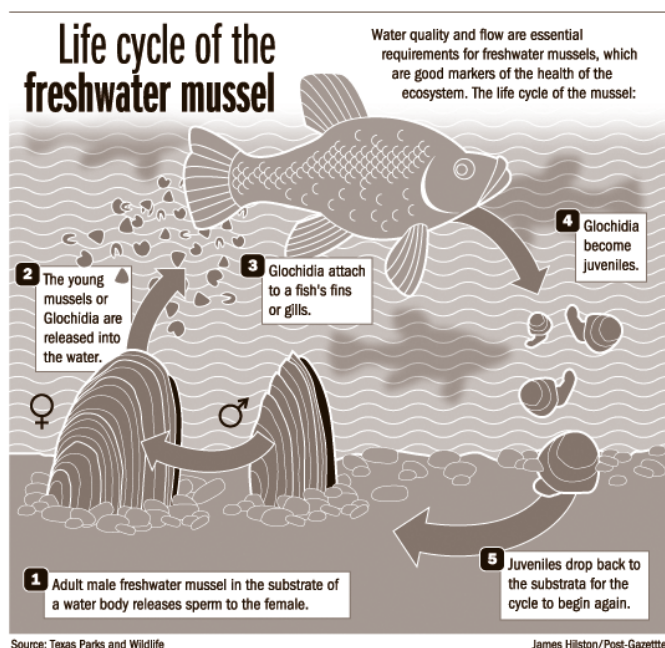


Fig. 4.4 Life cycle of mussels
(source: Texas Parks and Wildlife)

4.5 CONSLUSION

This paper aims to clarify the amount of time lag between habitat changes having a significant influence on the species diversity of fish, bitterlings and mussels. Results showed that species richness of bitterlings was best explained by a model consisting of location, age, transparency, mean grain size and DO 1 year ago. Species richness of mussels was best explained by a model consisting of flooding frequency and depth of mud 2 years ago. In contrast, species richness of resident fish and alien fish were significantly correlated with habitat conditions of the current year. Species richness of resident fish was best explained by low relative height, age, area and vegetation coverage, and that of alien fish was explained by a model consisting of low relative height, area, vegetation coverage and DO. Because mussels take time to get from a juvenile state to adulthood, the habitat condition when they are juveniles could be important for increasing and maintaining mussel abundance and richness. This implies the habitat condition, especially mud depth in

2009, could be considered as suitable for mussels in the Kizu River. In order to increase mussel richness, a stable period without big floods is required. At the same time, intermediate disturbance is required for maintaining suitable mud depth.

Chapter 5. Ecological evaluation of RSCC and its application to riverbed management

5.1 INTRODUCTION

River restoration has emerged as an increasingly important activity in developed countries to enhance biodiversity. Alternation of channel geomorphology due to reduction of disturbance influenced degradation of habitats and decrease of species diversity. Channel reconstruction carried out as a river restoration; e.g., channel alignment (widening or narrowing; Brierley and Fryirs, 2005), excavation of floodplain material to the river bottom level (Jahnig et al., 2009) and making meandering (Kondolf, 2006). However, some projects without reflecting potential river characteristics, experienced failures. Kondolf (2006) said that meanders have been created in many channel re-constructions on rivers that were not historically meandering, and in many cases, these meanders have subsequently washed out. For sustainable river management, development and application of river management practices requires knowledge of the natural range of morphological adjustment for

different river types (Thomson et al., 2001). In order to establish a scheme of river management aiming at maintaining a target riverbed geomorphology (Takemon, 2010), characteristic should be focused on historical changes with potential river, because erosion and deposition of riverbed or creation and maintenance of geomorphic habitats reflect historical changes of flow of water and sediment.

In this respect, geomorphic channel classification estimated by ecological function could be used as a powerful device for riverbed management. Thomson et al. (2001) said that all geomorphological classification a scheme will only have ecological relevance if the link between channel morphology and aquatic habitat is understood. However, previous studies on causal relationships among hydro-geomorphic conditions, habitat structure and biodiversity are not yet enough for planning such restoration works in the scene. Thus, this study aims at application of the method for ecological evaluation of RSCC to riverbed management.

Reach scale channel configuration (RSCC) in the Kizu River was classified into single, slightly wandering straight and sinuous, quite wandering straight and sinuous, bifurcated wandering straight and sinuous, and braided channels using geomorphic parameters, e.g., number of channels, sinuosity, channel width, slope, ratio of landscape (Fig. 5.1). A total of 116 reaches were divided into 8 channel types during 1948-2002. Single or slightly wandering channel types were characterized by narrow channel width and approximately straight vertical shape with considerable vegetation expansion. In contrast, braided channel types were characterized by a wide channel width and a significantly concave vertical shape with a low vegetation area.

And classified channel types were evaluated by biodiversity such as habitat diversity and species abundance of bitterling and mussel (Fig. 5.2, 5.3). Bifurcated wandering sinuous channels had maximum habitat diversity and soundness (diversity x total habitat abundance) (Fig. 5.2), and slightly wandering channels or straight channels that were often seen in the 2000s tended to have high abundance of bitterling and mussel (Fig. 5.3).

Originally, RSCC such as braided, meandering, wandering, or anastomosing and straight channels can be classified by hydraulic-geomorphic parameters such as

discharge and slope (Leopold and Wolman, 1957), depth-grain size ratio and width-depth ratio (Muramoto and Fujita, 1977), sediment load and lateral stability (Schumm, 1985). Thus, according to comparison of RSCC variations in the Kizu River with these relations, we could predict the possibility of channel changes in the future or find out geomorphic countermeasures.

The purpose of this study is to find out hydro-geomorphic parameters related to channel types in the Kizu River, and to determine target parameters to manipulate for higher biodiversity. And finally, we propose framework of riverbed management in the Kizu River.

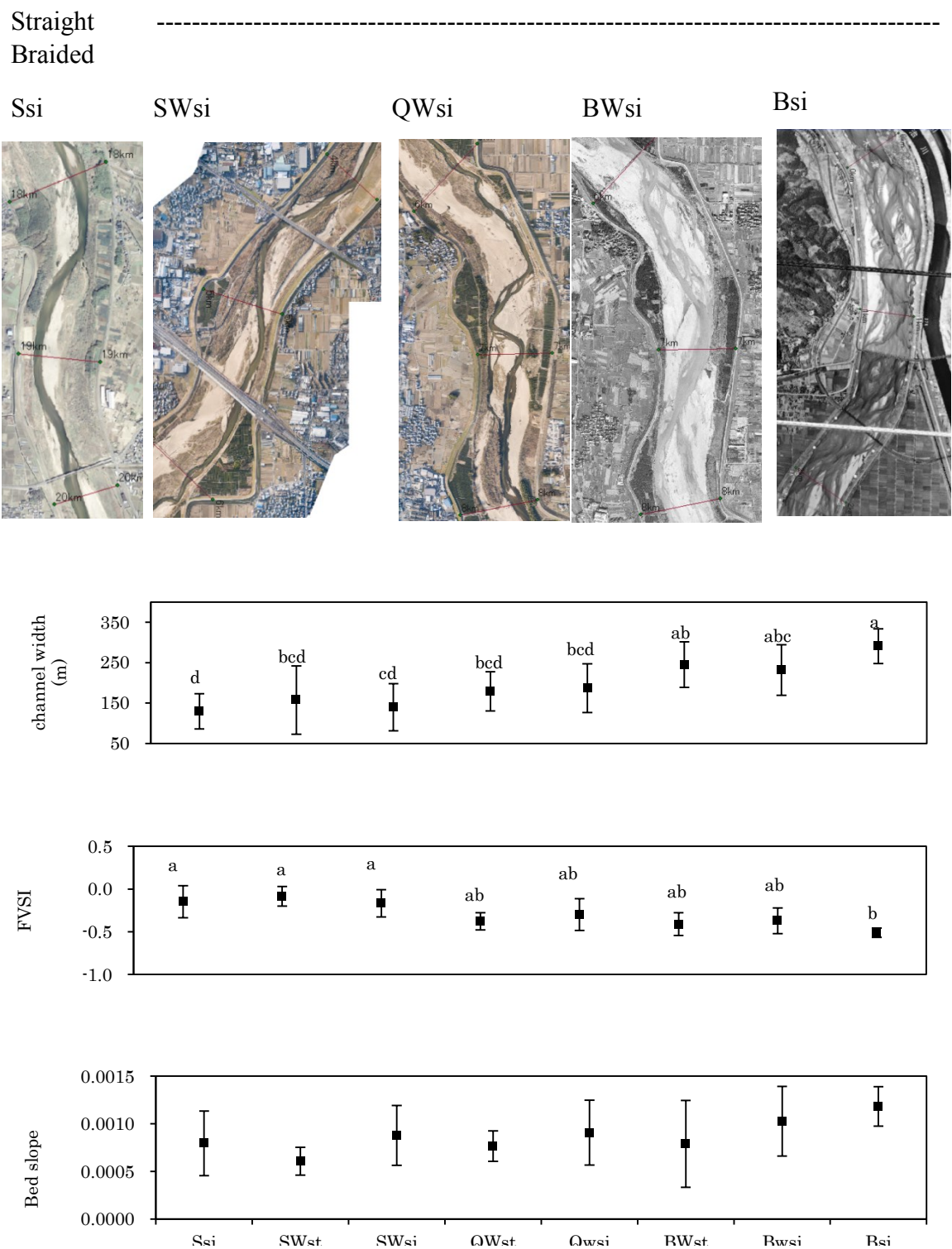


Fig. 5.1 Classification of RSCC in the Kizu River

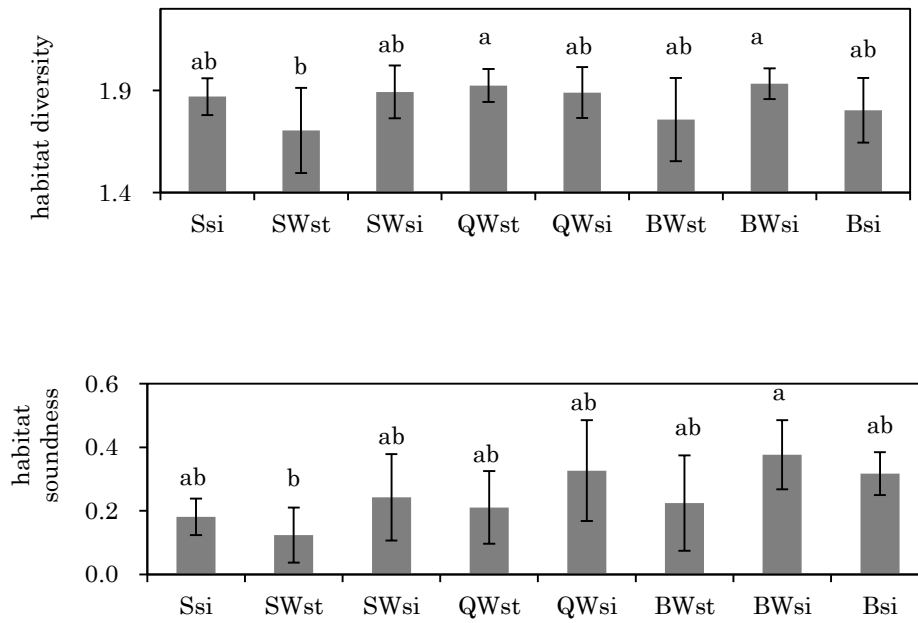


Fig. 5.2 Evaluated RSCC by habitat diversity and soundness

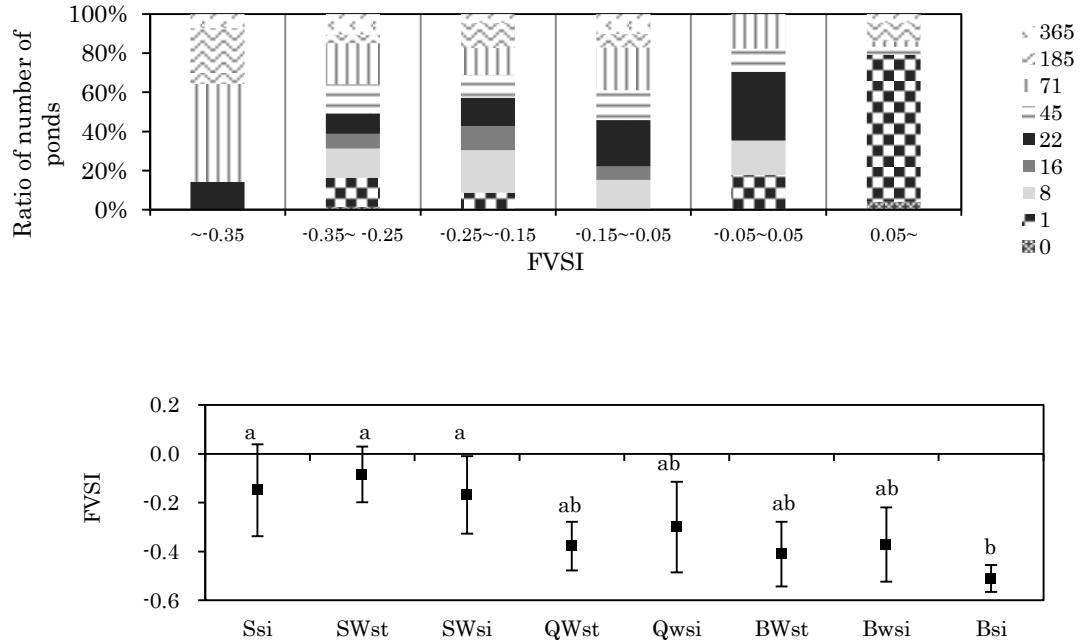


Fig. 5.3 (a) Evaluated RSCC using FVSI by habitat diversity and (b) relations between FVSI and channel types.

5.2 METHODS

5.2.2 Hydro-geomorphic parameters

RSCC in the Kizu River was related to dimension of hydro-geomorphic parameters; discharge and slope (Leopold and Wolman, 1957; Fig. 1.4a), depth/grain size ratio and width/depth ratio (Muramoto and Fujita, 1977; Fig. 1.4e), width/depth ratio and specific stream power (Burge, 2005). In dimension of discharge and slope, meandering and braided channel type was divided by formula $S = 0.013 Q_b^{-0.44}$. Area of alternative bar is $0.15 < (h/d)(B/h)^2)^{1/3} < 0.45$ in dimension of depth/grain size ratio and width/depth ratio. Specific stream power is pgQ_aS/w , where p is the density of water, g is the acceleration due to gravity, Q_a is the mean annual flood discharge, S is channel slope, and w is the bankfull channel width.

Data of discharge and depth was used by Yodogawa river offices (2011). Bankfull width (B) was defined by the boundary line where terrestrial vegetation begins along the stream margin (Fig 5.2). In chapter 2, active channel width was calculated by average width of active channel zone using aerial photos according to Hohensinner et al. (2011). Although bankfull width and active channel width have different definitions, active channel width was also considered, whether or not terrestrial vegetation exist; thus, values of active channel width were used as values of bankfull width. According to boundary of bankfull width, bankfull discharge (Q_b) used 250 m³/s of discharge that occurred 8 times per year, estimated using discharge during 10 years. Bankfull depth (h) was used by depth in bankfull discharge using levels higher 1 m than mean water level. Mean annual discharge (Q_a) was used by about 950 m³/s of discharge that occurred 1 time per 1 year. Bed slope used values of slope from when we used classification of RSCC in chapter 2. Grain size (d) used mean grain size (4.2 cm) according to Ashida et al. (2008), and it assumes no historical changes.

5.3 RESULTS

5.3.1 Relations of RSCC to hydro-geomorphic parameters

All channel types founded in the Kizu River were plotted within a restricted range of meandering channels in the dimensions of bankfull discharge and channel slope (Fig. 5.4). Because all channel slope in the Kizu River showed no significant difference (about 0.008 – 0.01) and bankfull discharge used just one value (250 m³/s) estimated over 10 years, there is no difference between RSCC variations in the Kizu River; i.e. the Kizu River is considered as a meandering channel, although it significantly changed during a period of 45 years.

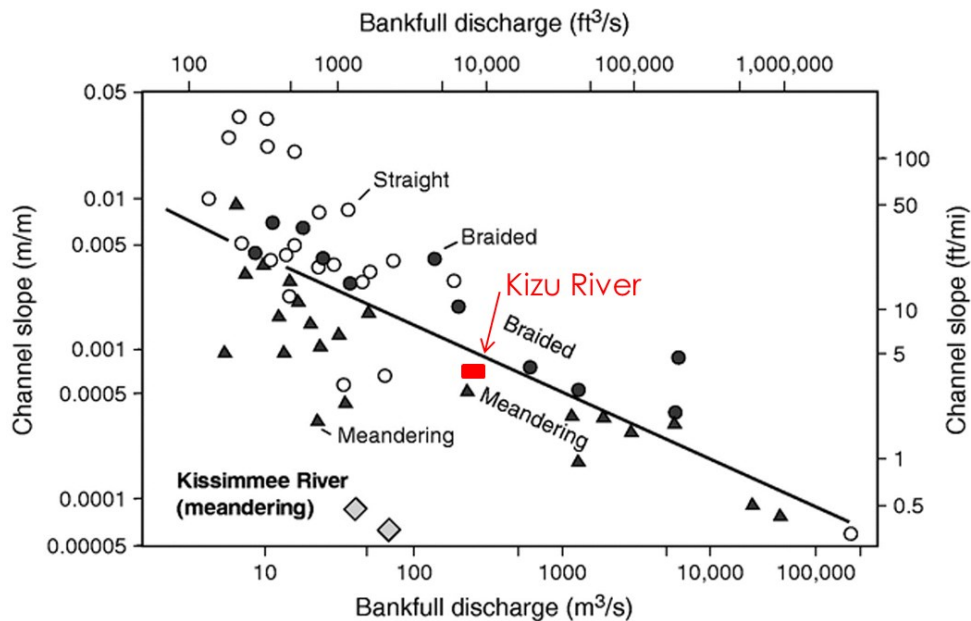


Fig. 5.4 Ranges of RSCC in the biplot dimension of bankfull discharge and channel slope (Latrubesse, 2008)

In the biplot dimension of depth/grain size ratio and width/depth ratio, channel types in the Kizu River were distributed as in Fig. 5.5. All channel types in the Kizu River were located in the alternative bar dimension, although channel types changed from braided to slightly wandering channels. Because we assumed that d is not different during a period of 45 years, the range of values of h/d was very narrow, and thus, channels in the Kizu River were located as only channel types having alternative bar dimension.

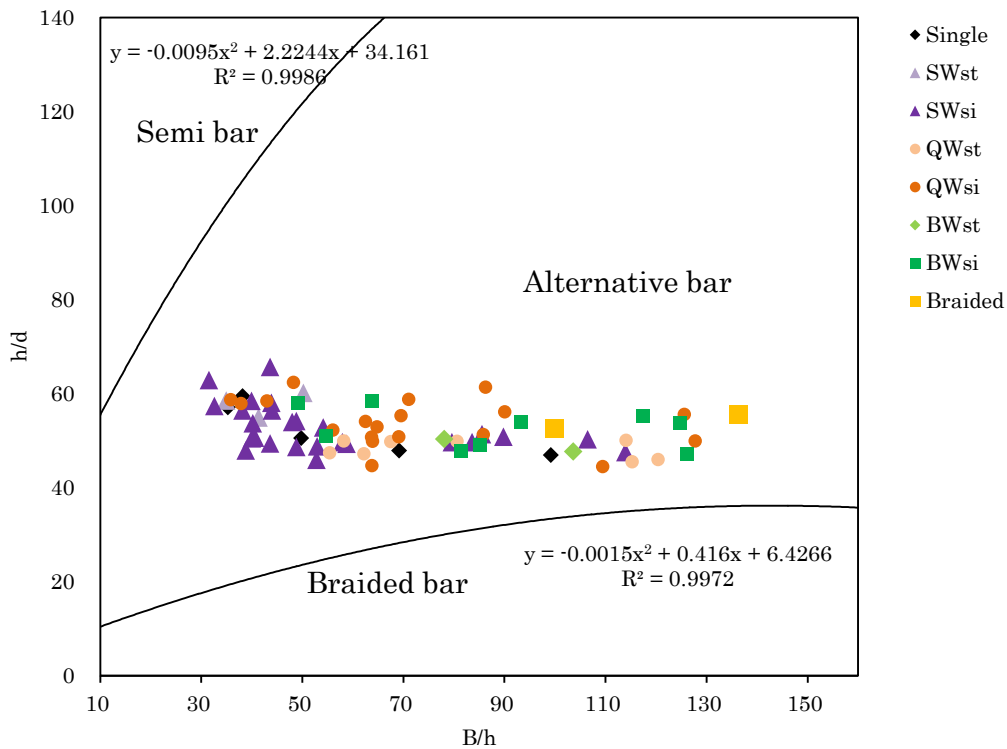


Fig. 5.5 Channel types in the Kizu River in the biplot dimension of depth/grain size ratio and width/depth ratio

We can see the channel types in the Kizu River related with dimension of width/depth ratio and specific stream power in Fig. 5.6. The channel types were located in the area of meandering and transitional wandering channel dimension. Fig. 5.6 (a) indicated plotted channel types and ranges of channel types of single (black), slightly wandering (violet), quite wandering (orange), bifurcated wandering (green) and braided channels (yellow).

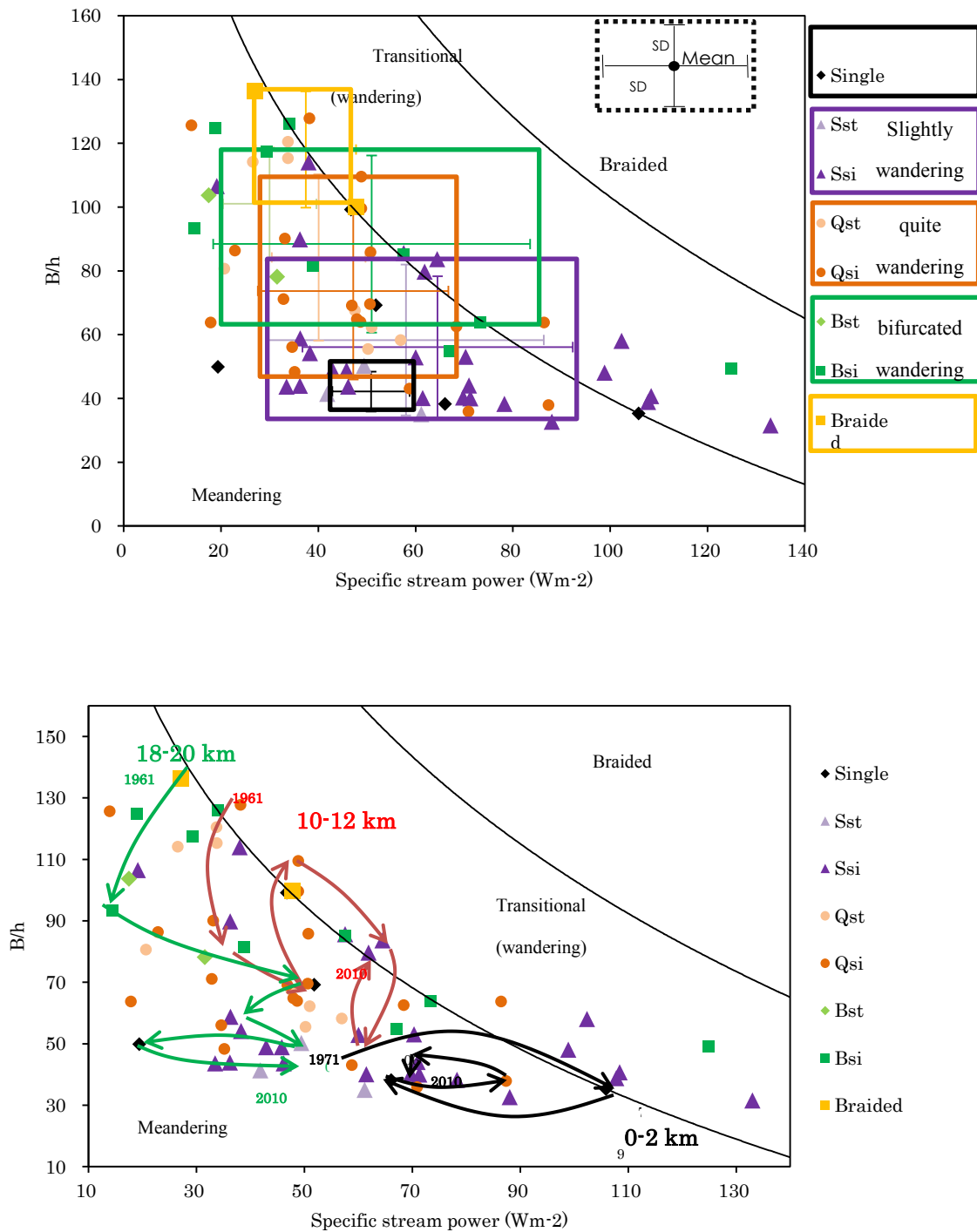


Fig. 5.6 (a) Distribution of each channel type within the biplot dimension of width/depth ratio and specific stream power in the Kizu River and (b) their historical changes in channel types, the plots of 0-2km, 10-12 km and 18-20 km correspond to those in lower, middle and upper reaches of the study area.

Ranges were square including mean values and standard deviation per same types (Fig. 5.6a). Range of single channels was located in the range of slightly wandering channels, and quite wandering channels showed higher range than slightly wandering channels. Range of bifurcated wandering channels was higher than single, slightly wandering and quite wandering channels. And the range of braided channels showed maximum values of B/h . In terms of specific stream power, the range of slightly wandering and bifurcated wandering channels appeared wider than that of single, quite wandering and braided channels.

Historical changes of channel types were shown in Fig. 5.6b. The upper site (18-20 km) moved from braided channel having the highest B/h to slightly wandering channel during 45 years with significant decreasing of B/h . The middle site (10-12 km) changed from a quite wandering channel to a slightly wandering channel with changes both in B/h and specific stream power. In contrast, lower site (0-2 km) moved from a quite wandering channel to a slightly wandering channel with significant changes of specific stream power and lowest changes of B/h .

5.3.2 Changing channels by increase/decrease of channel width

According to the distribution of channel types and their historical changes, we could predict resultant RSCC after manipulation of channel width (Fig. 5.7). Target channel types were focused on bifurcated wandering sinuous channels for maximum habitat diversity and soundness, and single, slightly wandering straight and sinuous channels for bitterling and mussel. Mainly, most of channel types in 2010 were distributed in the range of single and slightly wandering channels. Arrows meant their direction by changes of channel width. In the case of increasing channel width, channel types in the range of single and slightly wandering channel could be moved to the range of bifurcated wandering channels.

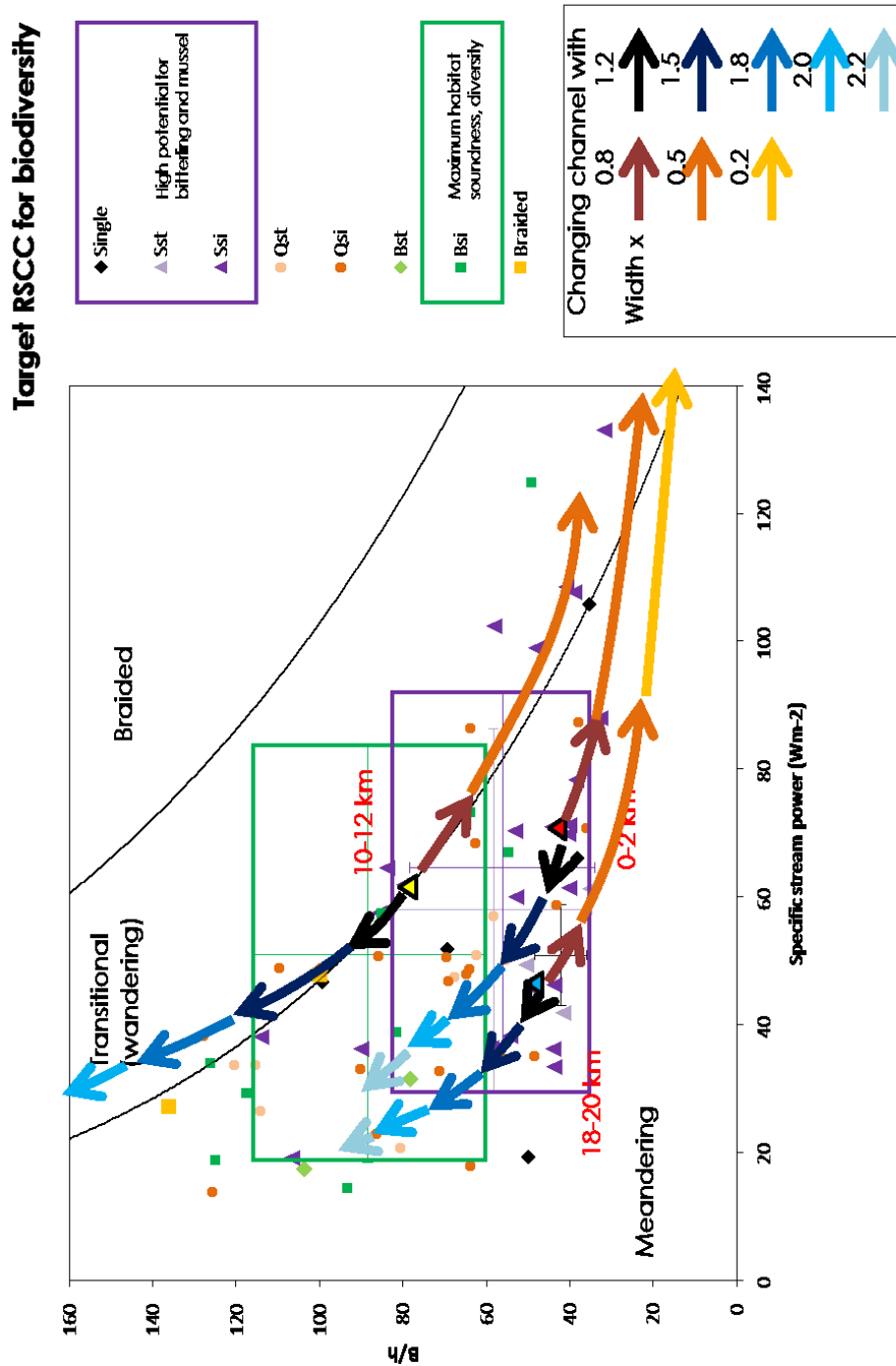


Fig. 5.7 Prediction method for resultant RSCC after manipulation of channel width. The countermeasure can be evaluated by the resultant RSCC plots in relation to the potential ranges for ecological functions.

5.3.3 Summary of suitable sediment volume of biodiversity

As for study of relations between habitat structure and RSCC, the volume of sediment transport required for increasing habitat abundance and divergence was estimated to be 40,000-60,000 m³/y (in chapter 2). As for study of relations among animals (bitterling and mussel), habitat condition and RSCC, a slightly lower volume of sediment (20,000-50,000 m³/y) would be acceptable for maintaining habitat suitability for bitterlings and mussels in lentic habitats in the Kizu River (in chapter 3). Thus, about 40,000-50,000 m³/y of sediment transport is required for increasing both habitat diversity/ soundness and bitterling/ mussel (Fig. 5.8).

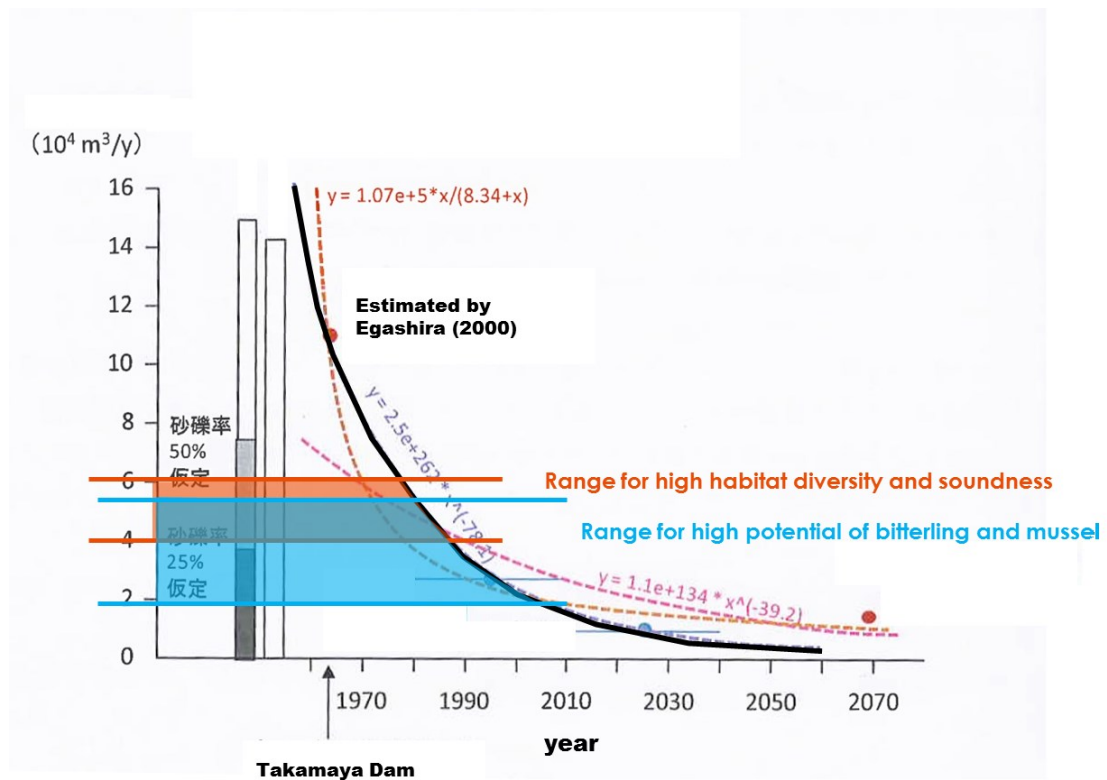


Fig.5.8 Volume of sediment transport required for biodiversity.

5.4 DISCUSSION

5.4.1 Proposal of short- term countermeasure for biodiversity

We should manage the river to improve river health and to prevent riverbed degradation. Especially for riverbed management method focused on riverbed, we could propose increasing channel width as a short-term countermeasure for biodiversity (Fig. 5.8). The middle site (10-12 km) was included in the range of slightly wandering (high potential of bitterling and mussel) and bifurcated wandering channels (maximum habitat diversity and soundness). In other words, this reach already could satisfy both habitat diversity and bitterling/mussel. Actually, according to Terada (2011), the middle site (10-15 km) showed intermediate floodplain vertical shape having a high number of active ponds and terrace ponds. In addition, Yodogawa River Bureau (2010) noted that bitterling and mussel were more detected in the middle site (7-26 km) than in the upper or lower sites. If we want to change the range of channel types from single and slightly wandering to bifurcated channel types just in the lower (0-2 km) and upper (18-20 km) sites, increasing channel width (about 1.8 -2.0 times) could have the possibility for changing them.

Some studies showed the effects of channel adjustment by comparison between restored sites and natural channel. Rohde et al. (2004) assessed the restoration success of river widening as a landscape approach. Restored site, near-natural, regulated site were compared by riparian landscape (vegetation) mosaic. They noted that river widening provide opportunities for re-establishing riparian landscapes. The widening mainly promotes pioneer stages and more complex mosaic than near-natural sites due to the limited size of widenings. Jahnig et al. (2009) analyzed effects of re-braiding on hydromorphology, floodplain vegetation, beetles and benthic invertebrates in mountain rivers based on restored and non-restored site. Restored site was implemented such as excavation of floodplain material to the river bottom level, initiation of one or two secondary channel, or development by fallen tree in the absence of bank fixations. Mesohabitats were classified into main and secondary channel, connected and disconnected side arm, standing water body. They said that restoration increases habitat diversity and availability of biota in floodplain

meshohabitat while the effects on aquatic microhabitats (substrate types, terrestrial plants, etc.) and assemblages were less obvious. And species richness, but not the species diversity, of floodplain vegetation and beetles increased following increased habitat diversity with no effects on benthic invertebrates. Thus, we could predict that channel widening has possibility of increasing habitat diversity with biodiversity. And other methods of channel adjustment: e.g., initiation of channels or graveled island, utilization of fallen tree, etc. also should be considered based on theoretical and experimental analysis.

5.4.2 Proposal of long-term countermeasures for biodiversity

In the case of the Kizu River, sediment replenishment was tested in the Nunome River below Nunome Dam (since 2004), in the Uda River below the Murou Dam (2006), and Hinachi Dam (2008) and Shorenji Dam (2009) in the Kizu River basin (Kantoush et al., 2010). Ock et al. (2013) said that these applications require a systematic development in the stages of planning and implementation, in particular, predicting flushing flows (magnitude, frequency and timing), determining quantity (amount added) and quality (grain size and source materials) of coarse sediment, and selecting effective implementation techniques for adding and transporting sediment in the fields.

According to this study, we could estimate quantity of suitable sediment supply as a long-term countermeasure for biodiversity. As for study of relations between habitat structure and RSCC, the volume of sediment transport required for increasing habitat abundance and divergence was estimated to be 40,000-60,000 m³/y (in chapter 2). As for the study of relations among animals (bitterling and mussel), habitat condition and RSCC, a slightly lower volume of sediment (20,000-50,000 m³/y) would be acceptable for maintaining habitat suitability for bitterlings and mussels in lentic habitats in the Kizu River (in chapter 3). Thus, about 40,000-50,000 m³/y of sediment transport is required for increasing both habitat diversity/ soundness and bitterling/ mussel (Fig. 5.8).

5.4.3 Framework of ecological riverbed management in the Kizu River

Reach-scale channel configuration (RSCC) could be used as a useful device for linkage between ecology and hydraulics. In case of the Kizu River, RSCC was classified into single, slightly wandering straight and sinuous, quite wandering straight and sinuous, bifurcated wandering straight and sinuous, and braided channels using geomorphic parameters, e.g., number of channels, sinuosity, channel width, slope, ratio of landscape. Single or slightly channel types had narrow channel width and higher floodplain vertical shape index (FVSI) than others with vegetation expansion. In contrast, braided channel types showed wide channel width and lowest FVSI with low vegetation ratio.

We evaluated the RSCC based on habitat diversity, and abundance of bitterling and mussel for applying to ecological riverbed management. Bifurcated wandering sinuous channels had maximum habitat diversity and soundness (diversity x total habitat abundance), and slightly wandering channels or straight channels were often seen in the 2000s and tended to have high abundance of bitterling and mussel (Fig. 5.3).

Finally, through linkage between classified RSCC and dimension of hydro-geomorphic parameters, we could determine short-term (increasing channel width about 1.8-2.0 times in upper and lower site) and long-term countermeasures (sediment supply about 4,000-5,000 m³/y) aiming at higher biodiversity. This framework could link among ecological function, geomorphology and hydraulics in consideration with habitat scale, reach scale and basin scale at the same time.

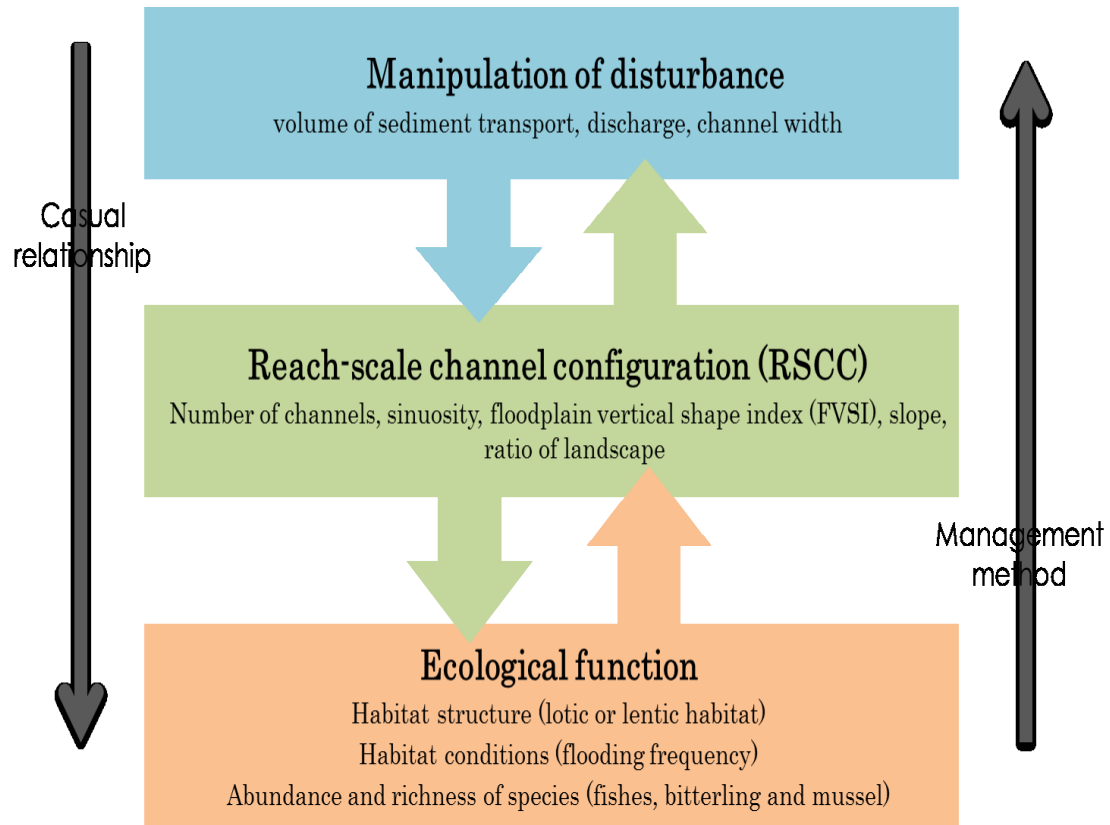


Fig. 5.9 Ecological riverbed management in the Kizu River

Appendix (General guideline for measurement of geomorphic parameters)

1. Measuring RSCC: aerial photos

All aerial photos were taken during low water depth. In this study, we divided the study area into 2 km units according to the mean wavelength of alternative bars (mean wavelength: 1.93 km, range: 1.6-2.6 km, Table. 2.5). The texture, shape and shadows were used to detect active channels, terraces with bush-land and woodland. In the aerial photos, various geomorphological parameters were calculated (Fig. a-1)

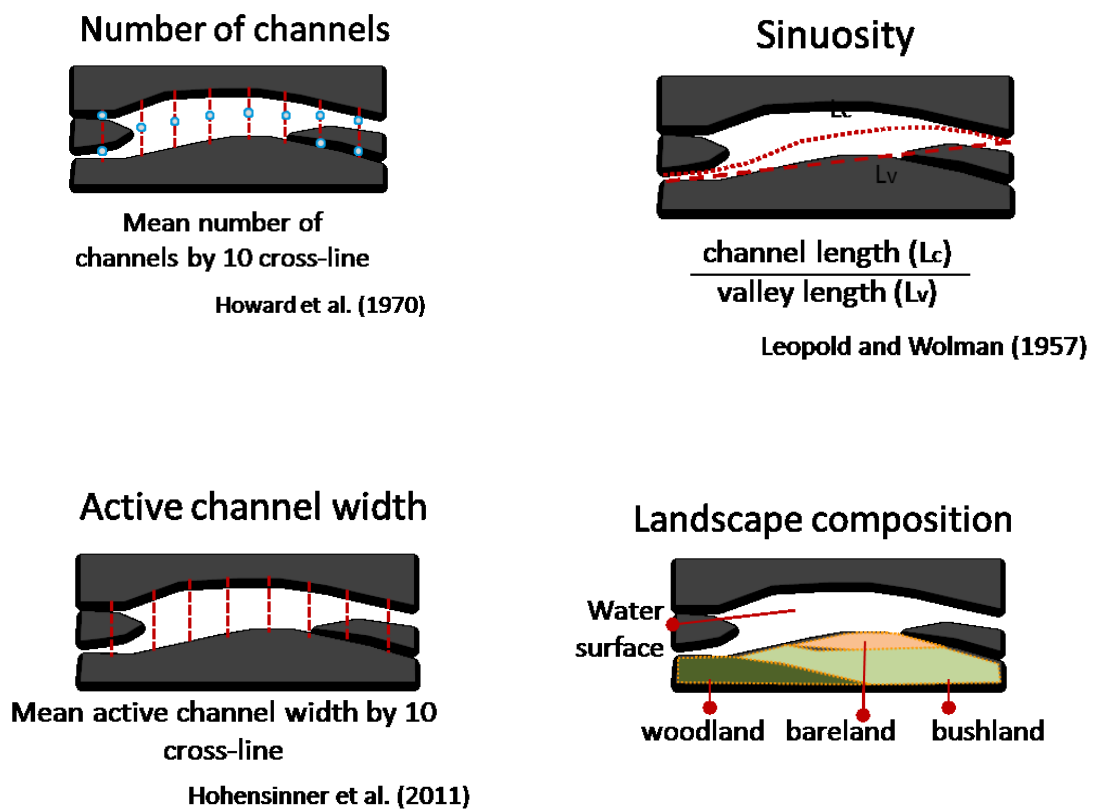
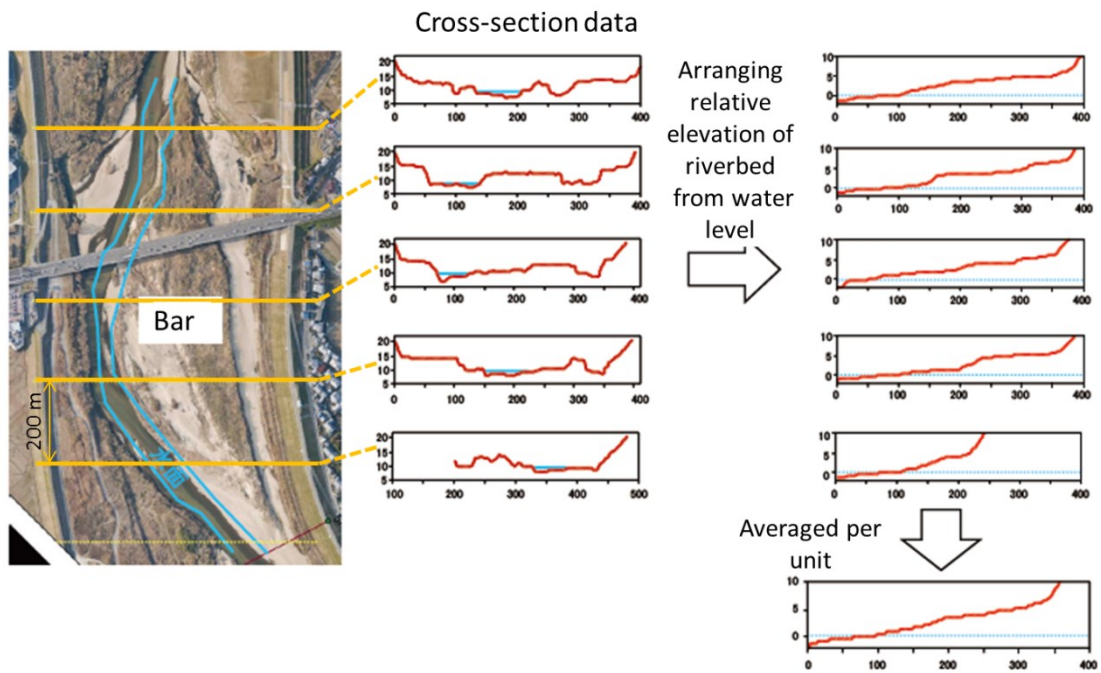


Fig. a-1 Calculation of reach-scale geomorphological parameters

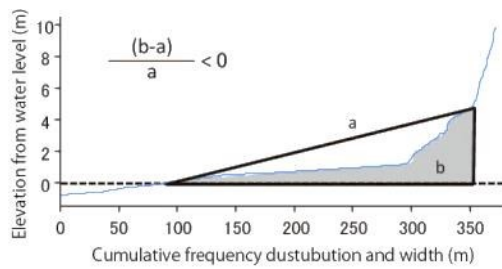
2. Measuring RSCC: cross-section data

We recommend similar or same period of cross-section data and aerial photo to compare or confirm two-dimensional and cross-sectional changes. FVSI was defined as a degree of convex or concave shape in the altitude distribution of the floodplain (Takemon et al., 2013); i.e. positive values of FVSI are reflected in a convex vertical shape, and the negative values in a concave vertical shape.

Method of measurement of FVSI was shown in Fig. a-2. FVSI is the difference of integral values of relative elevation of riverbed to normal water level and those of uniformly distributed elevation within a 2 km unit. Normal water level was calculated by mean water level by one dimension simulation using discharge data from 1970 to 2010.



(a) Concave shape



(b) Convex shape

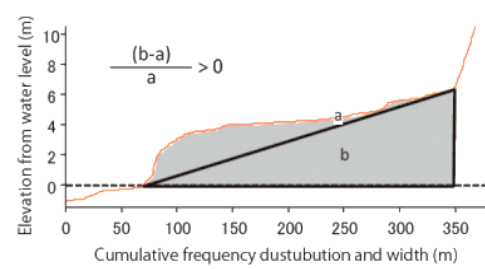


Fig. a-2 Methods of calculation of FVSI (Takemon et al., 2013)

3. Classification of habitat structure

Habitat parameter was classified based on the spatial classification of Habitatology introduced by Takemon (2010). Riffle was defined as shallow flow with rough water surface overflowing a lateral bar. In lentic habitats, bar-head wando was lentic water located at the bar head opening to the channel, and bar-tail wando was located at the bar tail. Active pond was isolated lentic water on the low flood plain and terrace pond was isolated lentic water on the terrace (Fig. a-3)

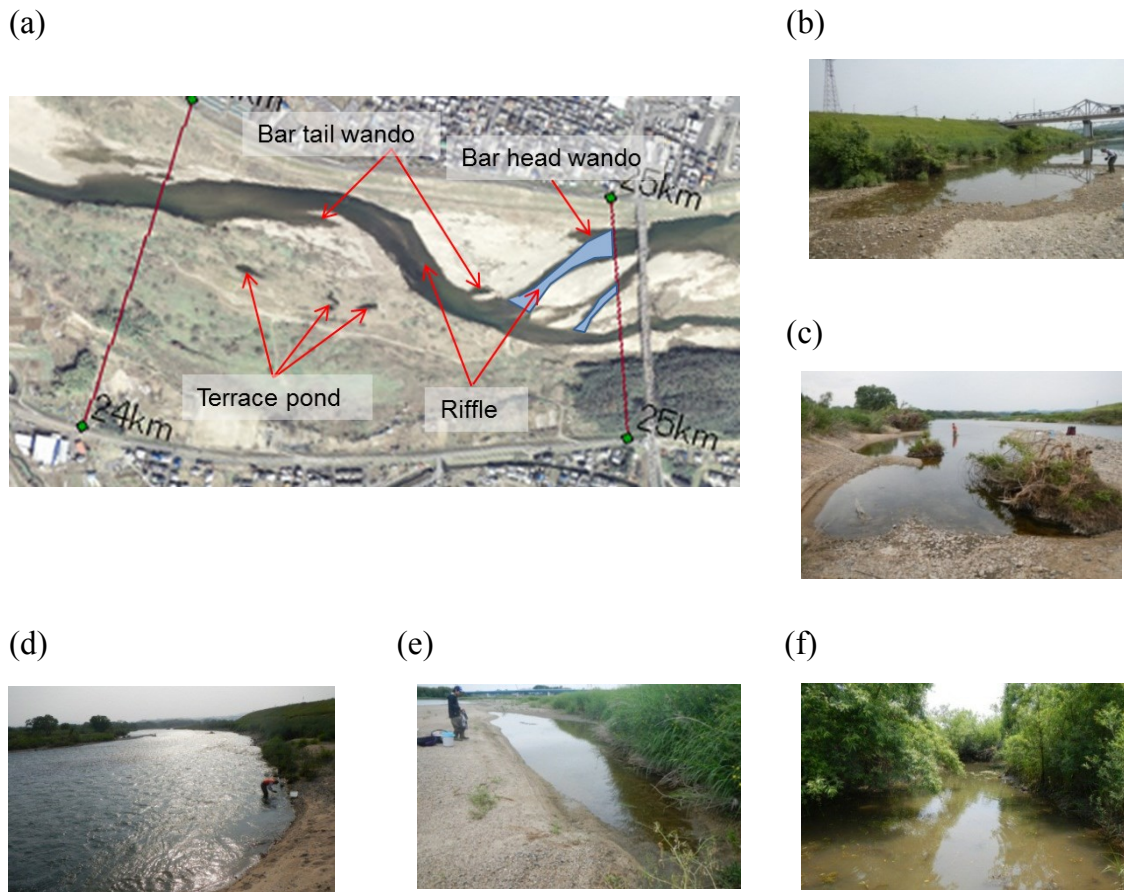


Fig. a-3 (a) Classification of habitat structure using aerial photo (b) bar-head wando (c) bar-tail wando (d) riffle (e) active pond (f) terrace pond

Chapter 6. Conclusion

This study aims at investigating interrelationships among RSCC, habitat structure and biodiversity and tries to develop river management methods through assessing the ecological conditions of rivers with hierarchical approaches in the Kizu River, a typical semi-natural sediment-rich river in Japan. This study described that RSCC in the Kizu River was classified, the RSCC variations were evaluated by habitat diversity/soundness and bitterling/mussel, and then ecologically evaluated RSCC was used to propose countermeasures for riverbed management using two methods; 1) sediment discharge required for biodiversity was estimated based on relations between ecologically suitable channel types and annual sediment discharge, and 2) geomorphic parameters for changing RSCC from current to suitable channel were proposed based on relations between RSCC variations and dimension of hydro-geomorphic parameters.

▪ Classification of RSCC and its historical changes in the Kizu River

Reach-scale channel configuration (RSCC) in the Kizu River was classified into single, slightly wandering straight and sinuous, quite wandering straight and sinuous, bifurcated wandering straight and sinuous, and braided channels. Single or slightly

wandering channel types were characterized by narrow channel width and convex floodplain shape with vegetation expansion. In contrast, braided channel types were characterized by wide channel width and significantly concave floodplain shape with low vegetation ratio. Braided or bifurcated wandering sinuous channels disappeared, whereas single or slightly wandering sinuous channels increased during a 65-year period in the Kizu River.

▪ **Evaluation of RSCC by habitat structure and biodiversity**

Classified RSCC variations were evaluated by habitat diversity and soundness based on historical aerial photo. Although braided channels showed the maximum habitat abundance of total habitat types, quite wandering straight channels had the maximum habitat diversity and bifurcated wandering sinuous channels had the maximum habitat diversity and habitat soundness.

RSCC variations were also evaluated by abundance of bitterling and mussel. Terrace ponds with flooding frequency of 8- 22 days per year had the most abundant bitterlings and mussels. Number of these terrace ponds tended to increase on slightly wandering channels having floodplain vertical shape index (FVSI) of -0.35- 0.5.

▪ **Proposal of countermeasures for riverbed management**

1) Sediment supply

At about 4,000-6,000 m³/y of volume of sediment transport was required to increase number of suitable channel types (quite wandering straight and bifurcated wandering sinuous channels) for habitat diversity and soundness.

Channel types (single and slightly wandering channels) after the 1980s of the Kizu River had a higher potential of habitat suitability for bitterlings and mussels than before. According to relations between annual volume of sediment transport and suitable period (after the 1980s), about 2,000-5,000 m³/y of sediment discharge was required for enhancing bitterling and mussel.

Thus, about 4,000-5,000 m³/y required for both habitat diversity and bitterling/mussel was proposed as a long-term countermeasure for riverbed management in the Kizu River

2) Channel width

RSCC variations were related to dimension of hydro-geomorphic parameters (slope and discharge, depth/grain size ratio and width/depth ratio, width/depth ratio and specific stream power). Among these dimensions, width/depth ratio and specific stream power could be well explained by RSCC variations in the Kizu River. This dimension can predict method for resultant RSCC after manipulation of channel width. The countermeasure can be evaluated by the resultant RSCC plots in relation to the potential ranges for ecological functions. We could propose increasing channel width about 1.8-2.0 times in upper and lower site as a short-term countermeasure.

▪ Additional comments for applying to riverbed management

1) Discharge for bitterlings and mussels: according to relations between habitat conditions (especially mud depth and flooding frequency) and bitterling/mussel, mussel need relatively stable habitat conditions; e.g., recent channel conditions that were stabilized had potential of mussel, and current mussel richness was significantly related to habitat conditions (which were stabilized due to low peak discharge during a period of 2 years) two years ago. However, no or low flooding frequency influenced negative relations with bitterling and mussel; e.g., ponds with no or low flooding tended to increase mud depth, and then mussel in mud may have difficulty breathing due to reduction of DO. That is, bitterling and mussel required stable conditions, but not excessively.

2) RSCC as indicator for prediction of habitat diversity: ecologically evaluated RSCC could be used as an indicator for prediction of habitat diversity when we implement simulations or experiments of riverbed changes. We could predict their habitat diversity or abundance based on information gathering with cases of other rivers.

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